Analysis of the construction waste management performance in Hong Kong: the public and private sectors compared using big data

Weisheng Lu[1], Xi Chen[1], Daniel Ho[1], and Hongdi Wang[1]
1 Department of Real Estate and Construction, Faculty of Architecture, The University of Hong Kong, Pokfulam, Hong Kong.

Abstract
There is an ongoing debate concerning the disparity between the public and private sectors in relation to construction waste management (CWM) performance: some argue that CWM performance between the two sectors should have no difference since they are under the governance of the same set of CWM related regulations, while others argue that public sector clients should perform better as they are subject to greater social scrutiny. Previous studies comparing CWM performance have suffered from insufficient quality data, leaving the debate on the CWM performance disparity largely inconclusive. Informed by the Coase Invariant Theorem, this research empirically compares CWM performance between public and private projects. It does so by using big data in the form of 2 million waste disposal records generated from around 5,700 projects undertaken in Hong Kong during 2011 and 2012. It is found that there is a notable CWM performance disparity between the public and private sectors, with contractors performing better in managing both inert and non-inert waste in public projects than they do in private projects. Furthermore, the interviews and case studies conducted as part of the research suggest that CWM transaction costs are not high enough to incentivize contractors to manage waste conscientiously and therefore other institutional arrangements, such as promoting the value of environment protection leadership, are critical for achieving superior CWM performance. The research therefore supports the corollary of Coase Invariant Theorem, which asserts that certain forms of institutions would improve CWM performance by reducing transaction cost even though both sectors are subject to the same set of CWM-related formal public policies.

Keywords: Construction and demolition waste, construction waste management, waste generation rate, performance, Coase Invariant Theorem, big data

Introduction
Either public or private clients sponsor construction work. The public sector, in the form of government departments and their subsidiaries, not only manage the economy and set and maintain standards for the construction industry, but also acts directly as a client for construction works (Hillebrandt, 1974) by developing institutional premises such as town halls, governmental offices, schools, hospitals, and public housing. Owing to the large size of its budgets and of the

complexities involved, the public sector is seen as indispensable to developing infrastructure projects for transport, energy, telecommunications, and water. In contrast, the private sector is primarily involved in the development of real estate such as private offices and residential buildings. In recent years, private client organizations have been increasingly involved in construction works that were traditionally developed by their public counterparts; this is known as public private partnership (PPP), which is defined by the U.S. National Council the National Council for PPP (2014) as "a contractual arrangement between a public sector agency and a private sector entity … in delivering a service or facility for the use of the general public".

There is an ongoing debate over whether public sector clients perform better than their private counterparts in CWM, or vice versa. One may argue that as public clients are subject to higher social and political control, they are less likely to practice illegal dumping and should therefore perform better in CWM than private clients. This presumption is partly supported by Tam et al. (2007), who discovered that private clients involved in private housing and private commercial projects tend to produce the highest wastage levels when compared with other types of projects. Hong Kong Advisory Council on the Environment's (ACE's) (2007) documents highlighted the two sectors separately in terms of CWM measures. Poon et al. (2013) explained further that public sector projects in Hong Kong have imposed more stringent contractual clauses to reduce waste generation and often provided financial incentives for waste reduction; while private sector projects emphasize time and cost efficiency. Under the Coase Invariant Theorem, as applied to construction management by Lai et al. (2008), there should be no difference in the performance between contractors working for different types of clients. This corollary of the Coase Invariant Theorem, which assumes zero transaction costs, speculates that even though construction clients from both sectors are regulated by the same set of CWM public policies and tend to hire contractors from the same labor pool, they would behave differently. However, the presumption of the difference in CWM performance between public and private sector client-contractor relationships has rarely been tested by empirical studies, despite its importance to not only do justices to contractors but also provide a useful reference for authorities when enacting and enforcing CWM-related public policies.

Moreover, research on CWM performance has commonly suffered from insufficient quality data to support an informed debate on CWM performance. Most of the empirical studies on CWM performance, measured by waste generation rate (WGR), have a relatively small sample or sampled relatively small sites due to the difficulties involved in conducting a survey on large-scale projects (Katz and Baum, 2011, Dahlbo et al., 2015). For example: Lu et al. (2011) measured waste generation in floor areas cordoned off by site managers in four sampled construction sites in Shenzhen, China, and revealed a WGR of 3.275–8.791 kg/m^2; Formoso et al. (2002) investigated the occurrence of material waste at 74 building sites located in different regions in Brazil with an average WGR of 27.6%; Tam et al. (2007) found a WGR of 15-27% through interviewing construction professionals at 19 sites in Hong Kong; and Yuan (2013) carried out a strength, weakness, opportunity, and threat analysis of CWM using data derived from governmental reports, waste management related regulations, literature review, and focus group meetings. Owing to the small samples, it is not surprising to see WGRs varying greatly from one study to another without any form of convergence. Results of such studies cannot therefore be utilized with a high level of confidence to substantiate the speculation that public sector clients perform better in CWM than their private sector counterparts, or the opposite.

This paper reports on the findings of an empirical study that seeks to test the hypothesis of the disparity of CWM performance between the public and private sectors. The research is contextualized in Hong Kong where a large set of data that has become available recently. This 'big data' covered around 5,764 sites, large and small, scattered over Hong Kong, which produced 2,212,026 waste generation/disposal records in the two consecutive years of 2011 and 2012. According to the Law of Large Numbers, the average of the results obtained from a large number of trials should converge to a certain value as more trials are performed (Sen and Singer, 1993). It is conjectured that the CWM performance of the public and private sectors could converge with big data and that it could provide a fuller picture of CWM in various projects, based on which more reliable conclusions can be drawn. The result shows there being a considerable disparity of CWM performance between the public and private sectors. It is further discovered that CWM transaction costs are not high enough to force contractors to undertake CWM conscientiously and therefore other institutional arrangements are critical for achieving superior CWM performance. This research provides empirical evidence to support the corollary of Coase Invariant Theorem.

The remainder of this paper is structured into five sections. Pursuant to this introductory section is an elaboration of the main concepts, including construction waste, waste management performance, and waste generation rate. Section 4 elaborates the theoretical lens for the paper, which is the Coase Invariant Theorem as applied to construction management by Lai et al. (2008). Section 5 describes a detailed description of the methodology. Big data is utilized to elucidate the CWM performance between the two sectors by examining different types of projects. Interviews and site visits were conducted to help understand the reasons behind the performance disparity. The sixth section presents the results, discussion, and findings. Conclusions and implications for further research are given in Section 7.

Construction and demolition waste

Construction and demolition (C&D) waste, sometimes simply called construction waste, is defined as the waste that arises from construction, renovation, and demolition activities (Kofoworola and Gheewala, 2009). It may include surplus and damaged products and materials arising in the course of construction work or used temporarily during the process of on-site activities (Roche and Hegarty, 2006). In Hong Kong, both terms are used to represent the surplus materials generated by site clearance, excavation, construction, refurbishment, renovation, demolition, and road works (Lu and Yuan, 2011). In this paper, the terms 'construction waste' and 'C&D waste' are used interchangeably to represent inclusively material waste from all construction activities without confining to a certain stage of construction, renovation, or demolition. Although C&D waste is often included as one of the forms of municipal solid waste (MSW), C&D waste is considered heterogeneous when compared to general MSW (e.g. household waste) or other industrial solid waste (ISW) (e.g. hospital waste or electronic equipment) (Lu et al., 2011). Construction is an environmentally unfriendly activity. Its waste often constitutes a prodigious portion of the total MSW that contributes to degradation of the environment (Lu and Tam, 2013; Boiral and Henri, 2012; Coelho and de Brito, 2012).

Construction waste can also be classified according to its composition. The European Waste Catalogue (EWC) classifies construction waste into eight categories such as concrete, bricks, tiles and ceramics; wood, glass and plastic; bituminous mixtures, coal tar and tarred products; metals, soil, stones and dredging spoil; insulation materials and asbestos-containing construction materials; etc. In Hong Kong, the composition of construction waste is divided into the two major categories: inert construction waste (ICW) and non-inert construction waste (non-ICW) (EPD, 2005). Lu (2013a) views the inert and non-inert dichotomy as a philosophy underlying the CWM system in Hong Kong, including its policies, regulations, and practices. The ICW comprises soft inert materials such as soil, earth, silt, slurry as well as hard inert materials such as rocks and broken concrete, while the non-inert materials include metals, timber, plastics and packaging waste (EPD, 2005). Owing to its inertia, non-combustibility, and less odorous nature, ICW can be used for land reclamation and site formation, and thus its negative impact on the natural environment is theoretically negligible (Lu, 2013a). The non-ICW is disposed of in landfills, which take the valuable land space in Hong Kong. Anaerobic degradation of this waste creates water, air and soil pollution by the production of CO_2 and methane. Citizens normally adopt a Not-In-My-Back-Yard (NIMBY) stance in siting these CWM facilities. It is therefore of paramount importance to manage construction waste properly and its performance should be unambiguously measured and closely monitored.

Waste generation rate (WGR) as a performance indicator

Waste generation rate (WGR) is widely used as an indicator to measure construction waste management (CWM) performance. WGR can be calculated by dividing the waste in volume (m^3)

or quantity (tons) by either the amount of virgin materials purchased, or the amount required by the design, or per m^2 of gross floor area (GFA) (Formoso et al., 2002). Methodologies adopted for obtaining data for estimating WGRs are diverse and typically include: direct observation (Poon et al., 2001); comparing contractors' records (Skoyles, 1976); questionnaire and telephone survey (McGregor et al., 1993); sorting and weighing the waste materials on site (Bossink and Brouwers, 1996); collecting data through consultation with construction company employees (Treloar et al., 2003; Tam et al., 2007); and tape measurement and truck load records (Poon et al., 2001, 2004). There are two prevailing approaches: classifying waste materials into different categories, or treating them as a whole. Many studies (e.g. Bossink and Brouwers, 1996; Treloar et al., 2003) investigated WGRs by differentiating material waste, while others (e.g. Poon et al., 2004) investigated C&D waste by treating the waste stream as a whole. All the studies derived a general rate such as volume (m^3) or quantity (tons) of waste generated per m^2 of GFA.

In view of the fact that not every project has a GFA but that they all have a contract sum, this research introduces a new WGR indicator:

WGR=Waste quantity/contract sum (ton/million US$) *Equation (a)*

This indicates the level of waste generation in producing every million US$'s worth of construction work. By using this indicator, it is possible to compare CWM performance across non-building projects (e.g. roads, and civil engineering development), which do not have a GFA as the denominator in the WGR equation. Ideally, secondary objective data should be used to calculate this WGR indicator to increase the accountability of the CWM performance measurement. Moreover, the data should be big enough to enable the calculation of a convergent WGR that can be accepted with a high level of confidence. It is well known that construction projects differ significantly from one project to another, each having a relatively long period for construction works. An empirical measurement of CWM performance, if just probing into a certain project or a certain window of time of the project, should be treated with caution when it is to be generalized to other projects.

WGR, as an indicator of CWM performance, is considered the consequence of different causal factors. Bossink and Brouwers (1996) suggested that the factors include different construction techniques, work procedures, and common practices. By investigating WGR, one can link the CWM performance to these causal factors and provide quantitative information for benchmarking CWM practices across different projects (Lu et al., 2011). Lu and Tam (2014) used WGR and conducted an inter-jurisdiction analysis of the relationships between CWM performance and these causal factors. The underlying thinking of their study was that the causal factors would be different from one economy to another, which in turn explains the CWM performance disparity. The presumption is that the causal factors are the same intra-jurisdictionally, as they are fostered by certain profiles that epitomize the jurisdiction (e.g. CWM related strategies, regulations, and public policies). Nevertheless, CWM performance disparity caused by client-contractor relationships, even within the same jurisdiction, has been noticed (Tam et al., 2007) and increasingly debated by practitioners and policy-makers, although it has received scant attention from researchers.

The Coase Invariant Theorem applied to CWM

The theoretical lens for the paper is the Coase Invariant Theorem as applied to construction management by Lai et al. (2008). The Coase Theorem, first expressed by Stigler (1987), has two versions that can be labeled as the 'Invariant Theorem' and the 'Optimality Theorem' (Cheung, 1991). According to Lai et al. (2008), the Invariant Theorem can be described as: "Given: (a) zero transaction cost, and (b) clearly defined property rights, resource allocation would be identical irrespective of (and therefore 'invariant' to) the [way] rights and liabilities are assigned". In other words, the pattern of input allocation and mix, output mix and the like would not be affected by the applicable pattern of rights and obligations. However, it is hard to find the two antecedents in reality, and the Coase Theorem is thus often criticized for being almost always inapplicable in economic reality. Partly for dealing with the logical fallacy of previous arguments denying the applicability of the Coase Theorem, Lai et al. (2008) developed the corollary of the invariant theorem "Where transaction cost is not zero or property rights are unclear or poorly defined, the assignment (pattern) of rights and liabilities would affect (the pattern of) resource allocation". While it is true that zero transaction cost and clearly defined property rights cannot be found in reality, the corollary helps examine which 'assignment (pattern) of rights and liabilities' (e.g. the law, governance and institutions, and contractual arrangements) will improve/reduce efficiency in allocating resources (e.g. qualities and qualities of input and output) through reducing/increasing transaction costs. The Coase Invariant Theorem thus provides the theoretical lens for examining potential CWM performance disparity with a view to identifying the 'assignment (pattern) of rights and liabilities' that reduces transaction cost and/or improves efficiency of CWM.

By transposing Coase's wheat farming and cattle raising examples to CWM, the relevant input becomes the money, labor, and machinery necessary to reduce, reuse, recycle, and finally dispose of C&D waste, while the output is the inert or non-inert C&D waste that will be disposed of at government waste management facilities such as landfills and public fills. CWM can be perceived as a production function, the only difference being that the more resources allocated, the less output will be produced and the better the CWM performance will be. Given its negative impacts to the natural environment, as a public good, construction waste is often heavily regulated by authorities using public policies (Lu and Tam, 2013). Government should enhance their role: enforcement of environmental law and furtherance of using construction waste as raw material for manufacture (Rodríguez et al., 2014). Here, 'public policy' is an inclusive term, which may comprise CWM related ordinances, regulations, codes of practice, and initiatives introduced by government or its executive arms. The orthodox wisdom is that contractors, which are the perceived polluters who are responsible for the waste generated, should all behave the same under the same set of CWM public policies. Therefore, the main hypothesis is:

H1: There is no disparity of construction waste management (CWM) performance between the public and private projects

If the hypothesis is denied using big data and more robust methodological instruments, explanations to the disparity should be sought by examining the institutional arrangement that reduce/increase transaction costs.

Research methodology

The 'big data' for comparing waste generation rates

Based on the 'polluter pays principle', a Construction Waste Disposal Charging Scheme (CWDCS) has been enacted in Hong Kong since 2006. In line with the CWDCS, a construction contractor is charged HK$ 125 for every ton of non-inert construction waste (non-ICW) it disposes in landfills; HK$ 100 per ton for mixed inert construction waste (ICW) and non-ICW accepted by off-site sorting facilities (OSFs); and HK$ 27 per ton of waste consisting entirely of ICW accepted by public fill reception facilities (PFRFs). By following the CWDCS, contractors have to dispose of their construction waste at designated government facilities, if not otherwise properly reused. For every truck of construction waste received at the facilities, the Hong Kong Environmental Protection Department (HKEPD) records the information. This practice leads to around 1.1 million disposal records per year, which form the 'big data' recording the project properties, client types, and waste disposals in a well-structured manner (see Fig. 1 for an excerpt of the data). For example, the big data recorded that a certain vehicle (labelled by vehicle plate no.) transported a certain amount of construction waste (weight-in, weight-out, and net weight) in a certain time (time-in, and time-out) to a specific facility.

Facility	Date of transaction	Vehicle No.	Account No.	Chit No.	Time-in	Time-out	Waste depth (meter)	Weight-in (tonne)	Weight-out (tonne)	Net weight (tonne)
MW--PFRF	16/10/14	GM1*91	7020693	12661474	09:24	09:26	0.00	21.86	12.92	8.94
MW--PFRF	16/10/14	JG8*5	7015857	12247571	09:27	09:30	0.00	22.54	14.67	7.87
MW--PFRF	16/10/14	GM1*91	7020693	12661475	10:37	10:39	0.00	23.27	12.90	10.37
MW--PFRF	16/10/14	JG8*5	7015857	12247572	10:40	10:42	0.00	20.89	14.67	6.22
MW--PFRF	16/10/14	PG3*20	7018704	12526981	11:02	11:04	0.00	24.27	13.80	10.47
MW--PFRF	16/10/14	PG3*20	7018704	12526982	11:14	11:16	0.00	24.70	14.13	10.57
MW--PFRF	16/10/14	PG3*20	7018704	12526983	11:33	11:35	0.00	24.19	14.28	9.91
MW--PFRF	16/10/14	GM1*91	7020693	12661476	11:42	11:43	0.00	22.14	12.88	9.26
MW--PFRF	16/10/14	PG3*20	7018704	12526984	11:46	11:48	0.00	24.50	14.10	10.40
MW--PFRF	16/10/14	GM1*91	7020693	12661477	13:55	13:58	0.00	21.90	12.86	9.04
MW--PFRF	16/10/14	RY7*61	7018206	11074859	15:11	15:14	0.00	24.02	14.65	9.37
MW--PFRF	17/10/14	PG3*20	7019130	12585329	09:12	09:15	0.00	23.55	11.94	11.61
MW--PFRF	17/10/14	GM1*91	7019130	12585334	09:23	09:25	0.00	24.12	12.83	11.29
MW--PFRF	17/10/14	PG3*20	7019130	12585330	10:16	10:19	0.00	22.77	11.90	10.87
MW--PFRF	17/10/14	GM1*91	7019130	12585335	10:20	10:22	0.00	22.88	12.82	10.06
MW--PFRF	17/10/14	GL4*20	7018618	11346405	10:50	10:53	0.00	23.86	14.51	9.35
MW--PFRF	17/10/14	PG3*20	7019130	12585331	11:12	11:14	0.00	23.92	11.87	12.05

Fig. 1 Screenshot of some typical transaction records in the set of 'big data'

The waste is generated from various projects, each with a unique billing account number linking the disposal record to the specific project. Big data is composed of digital information, including unstructured and multi-structured data, often derived from interactions between people and machines such as web applications, social networks, genomics, and sensors (Arthur, 2013). According to Cappucio (2010), big data has the characteristics of volume, velocity, and variety: volume means large quantities of data, usually larger than that can be processed using traditional tools; velocity means that data have an ongoing flow and a fast speed coming into the organization; and variety in big data is that traditional structured data are now able to be joined with semi-structured and unstructured data. All these characteristics are evident in the waste disposal records.

Data analysis

Through analyzing big data, researchers aim at identifying some 'latent knowledge' (Agrawal, 2006) or 'actionable information' (WEF, 2010), which can be incorporated in future decision-making. Aside from the technical and methodological challenges, one premise of using big data is that the larger data volume will alleviate the potential bias in small data and provide a fuller picture so as to have a closer claim on objective truth. While the ability to gather, store, access, and analyze data has grown exponentially over the past decade (Shah et al., 2012), processing big data does not mean disregarding traditional methodologies such as statistical analyses or data mining (Kantardzic, 2003; Fayyad, 1996; Clifton, 2010); too often, articles on big data misleadingly associate it with buzzwords such as pattern finding algorithms, unattended machine learning, or artificial intelligence. In this research, the big volume of data is examined by traditional simple statistical analyses to find out whether there is a CWM performance disparity between public and private projects. These include the analyses of their distributions (e.g. normal distributions or skewed distributions), means, medians, and standard deviations using *R,* which is an open source statistical analytical software program (*R* Development Core Team, 2008)

Interviews and field studies

Case studies were conducted to provide qualitative date to deepen the understanding of CWM practices in Hong Kong gleaned from the big data analyses. Similar to the tenet underlying big data thinking, in choosing the case projects, they should be sizable ones with a relatively long period of construction time to allow for a comprehensive investigation of CWM practices. The project types should be representative and the interviewees should have ten years of experience in managing construction waste. From the information provided in Table 1, it can be seen that four of the case study projects were buildings while the rest were infrastructure projects. Five of the projects were sponsored by public clients, including Hong Kong Housing Authority (HKHA) (e.g., public housing), the Mass Transit Railway Corporation (MTRC) (e.g., tunnel and stations), and the Architecture Services Department (ASD) (e.g., schools, offices, and other institutional buildings). Each case study was conducted by three research assistants who made non-participant observations on the construction site and asked questions of interviewees concerning actual CWM behavior (e.g., reduction, reuse, recycling, and disposal) and their perception of current CWM practices in Hong Kong's construction industry. One may notice the diverse descriptions of the roles who were designated for CWM in Hong Kong; this reflects the industry's struggle with designing a post called waste manager. Interview questions were organized surrounding aspects including their daily CWM practices, the major concerns (e.g. costs), their solutions (e.g. 3R), and their suggestions to the Government. Costs and benefits are critical data to be solicited but the former was not specifically classified as production cost or transaction cost. It is unfair to let the practitioners to understand the terminology. These interviews and field studies provided valuable insights from senior players as qualitative data to be triangulated with the data from the statistical analyses and the case studies.

Table 1 Profile of the surveyed case studies

Project No.	**Project type**	**Public/ Private**	**Contract Sum (HK$)**	**Interviewee**	**Date of Survey**
A	MTRC Tunnel (civil)	Public	28,105 million	Safety manager	19 September 2013
B	Superstructure of New public housing (building)	Public	102.343 million	Site manager	23 October 2013
C	MTRC (building services)	Public	272 million	Site safety manager and public relationship (PR) staff	26 November 2013
D	New Public building	Public	213 million	Site manager	14 March 2014

	(foundation)				
E	MTR station (building)	Public	Unknown	Corporate social responsibility (CSR) and sustainability manager	15 November 2013
F	Private building renovation (M&R)	Private	Less than 1 million	Foreman	15 April 2014

Data analyses and results

Project profile: public and private compared

Fig. 2 shows that in the two years of 2011 and 2012, a total of 5,764 projects disposed of construction waste in various government CWM facilities. They left over 2,212,026 waste disposal records (see Fig. 1) in the HKEPD, which form the 'big data' for comparing CWM performance between the private and public sectors. Amongst them, 1,084 (19%) were public projects and 3,143 (54%) were private projects. A large number of projects (1,537 or 27%) were classified as 'unclear' and not used as part of the analyses because they only had a billing account without specific linkages to a public or private client and did not have any specific project information (e.g. project type, GFA, or contract sum). The reason for this is that, in order to save transaction costs for minor construction works of less than HK$ 1 million, one waste disposal account can be used for a number of contracts without the need for contract details to be submitted by the account applicants. Specific project information was thus only available for construction contracts with a value of HK$ 1 million or more.

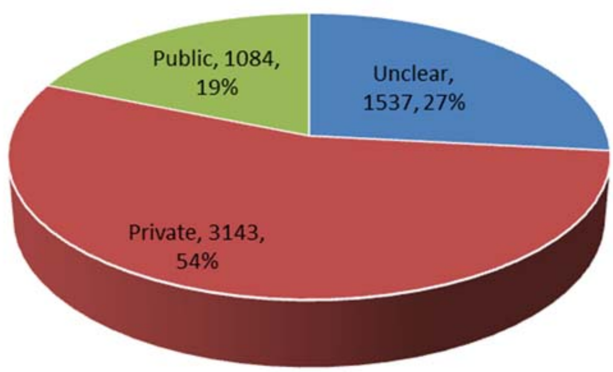


Fig. 2 Number of projects by sectors that disposed of C&D waste in 2011 and 2012

Fig. 3 illustrates the contract sums of the public and private projects that have disposed of waste in government CWM facilities in 2011 and 2012. Judging by their total contract sums, the private sector initiated more than half of the projects but the average contract sum of the public sector projects (266.82 b/1,084) is larger than that of the private sector projects (330.25 b/3,143). This is in accord with the belief that Hong Kong's construction industry, in one of the freest market economies in the world (Friedman and Friedman, 1990), has both a strong public and private sector (Lu, 2013b). This also supports the generally held belief that public sector clients mainly sponsor complex, large budget projects.

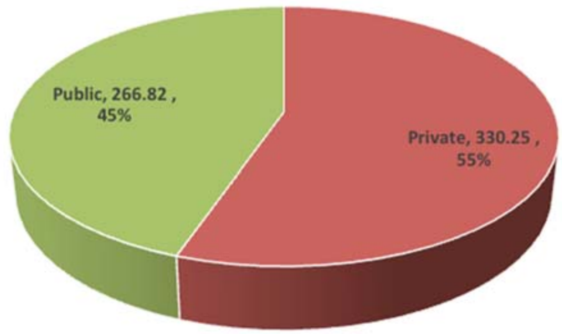
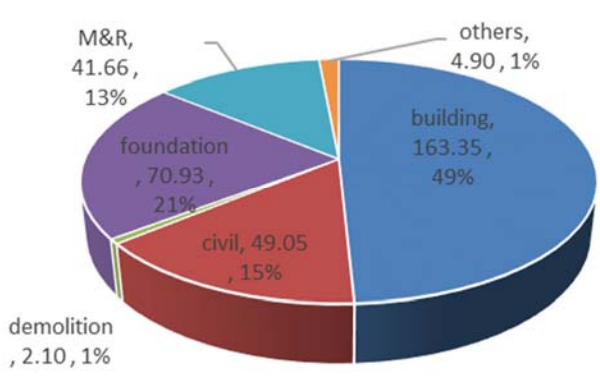
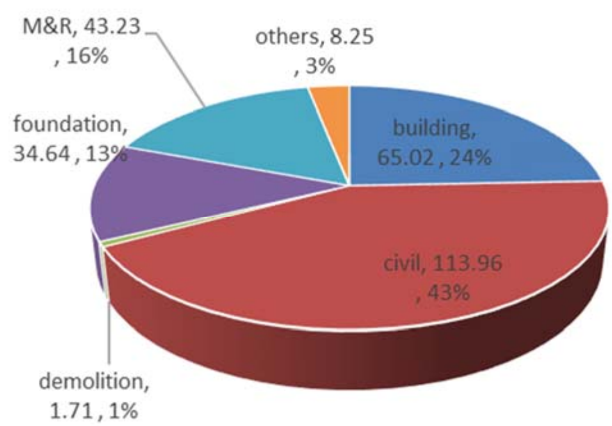


Fig. 3 Contract sums (billion HK$) of projects by sector that disposed of C&D waste in 2011 and 2012

Fig. 4 further illustrates in detail the distribution of different types of projects in the private and public sectors. It comes as no surprise that private sector clients are primarily involved in building development (163.35b, 49% of the total private projects, Fig. 4[a]) while their public counterparts are mainly involved in civil works (113.96b, 43% of the total public projects, Fig. 4 [b]). However, it is somewhat surprising to see that the private sector in Hong Kong is also heavily involved in civil works (49.05b, 15% of the total private projects, Fig. 4[a]), e.g. the linking facilities between MTR stations and their estate villages. Both sectors had a considerable portion of foundation works (70.93b for the private and 34.64b for the public sector) and maintenance and renovation (M&R) works (41.66b for the private and 43.23b for the public sector).



(a) The private sector



(b) The public sector

Fig. 4 Contract sums of projects that disposed of C&D waste in 2011 and 2012

Overall WGRs of private and public projects

Noise reduction was accomplished by removing projects with unreasonable WGRs, which resulted in ten projects with a WGR larger than 10,000 t/mHK$ being removed from the dataset, leaving 4,217 projects in the sample. The calculations of WGRs are all based on the new sample profiles as shown in Table 2 below. Fig. 5 is an illustration of the WGRs of all 4,217 projects in 2011 and 2012 by sector. The figure was produced by first calculating the WGRs of individual projects using *Equation (a)*, and then plotting the WGRs in a 2D axis system. It can be seen that the majority of WGRs fall in a range of 0.1 to 100 t/mHK$ and are randomly dispersed with no discernable pattern.

Table 2 New project profiles after noise reduction (Private vs Public)

	Private		Public	
	Project number	Contract sum (b HK$)	Project number	Contract sum (b HK$)
Building	504	163.35	122	65.02
Civil	197	49.04	319	113.96
Demolition	242	2.09	39	1.71
Foundation	428	70.93	121	34.64
M&R	1,693	41.66	426	43.23
Others	69	3.16	57	8.26
Total	3,133	330.24	1,084	266.82

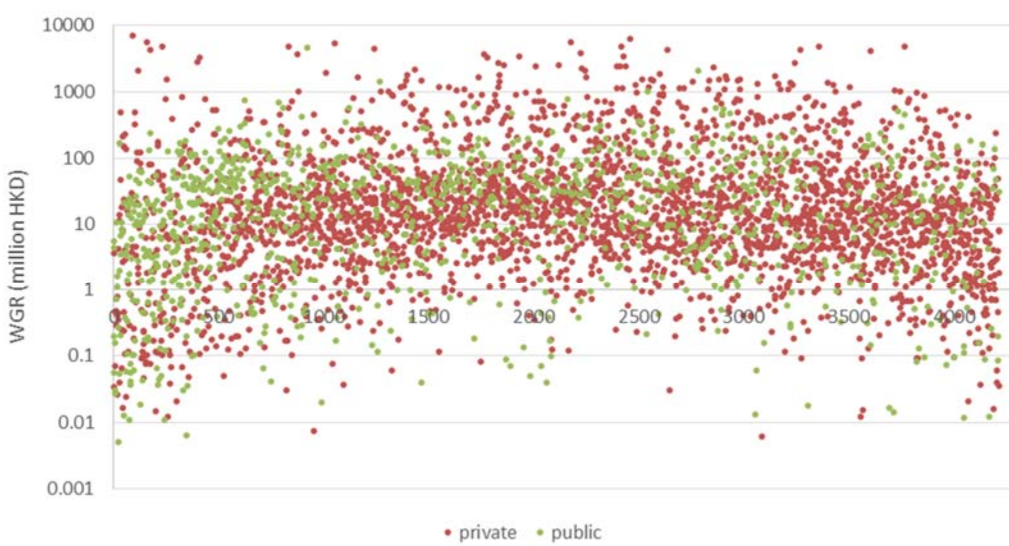


Fig. 5 WGRs of private and public projects

Fig. 6 presents the WGRs by ranking them from the smallest to the largest within their respective sectors and plotting them in the same 2D axis system. The result is not two continuous curves, but rather 4,217 discrete dots, each representing the WGR of a specific project. The total number of projects (4,217), private projects (3,133), and public projects (1,084) all remains unchanged but the WGRs are organized in a more orderly fashion. For the best case, a private project generated virtually no waste at all while for the worst case a private project generated 7,115 ton of construction waste in producing every million HK$'s worth of construction work. For the public projects, the best case project generated virtually no waste while the worst case project generated 4,648 ton of construction waste in producing every million HK$'s worth of construction work.

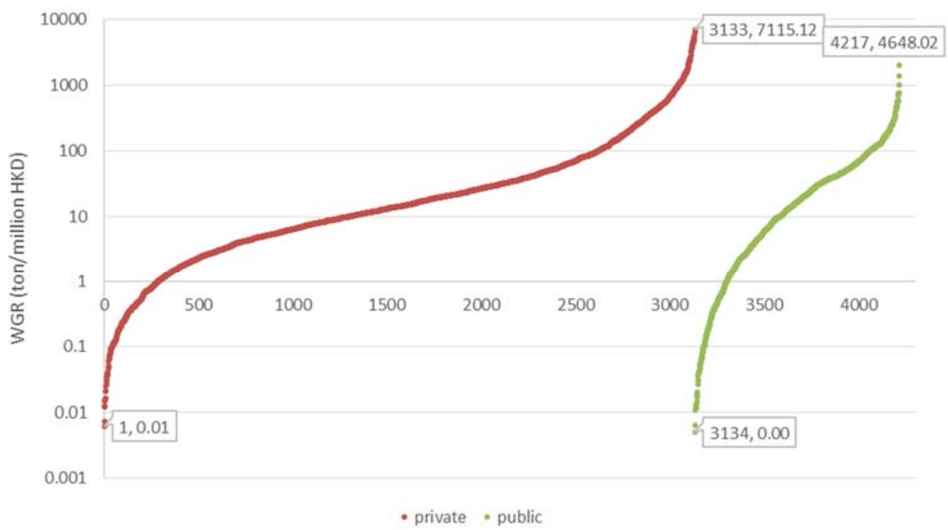


Fig. 6 WGRs in 2011 and 2012 ranked (private vs public)

Fig. 7 is a histogram of WGRs for overall, private, and public projects created by using *R*. The means of WGRs and the standard deviations (SD) of the projects in Table 3. It can be seen from Fig. 7 that the curves are far from a Normal Distribution but very close to a Skewed Distribution. This encourages us to try the three Skewed Distributions as the Log-Normal Distributions using *R*. At the core of the trials is the natural logarithm of WGR, i.e., *ln(WGR)*. Fig. 8 shows the histograms of the *ln(WGR)* for private, public, and overall projects, which tend to be Normal Distributions. Most *ln(WGR)*s are concentrated around the median of *ln(WGR)*s, which means most WGRs are scattered around the median of WGRs in a Log-Normal or similar to Log-Normal Distribution. Based on the process to try the Skewed Distributions as the Log-Normal Distributions, the median of private WGRs is 14.31 t/mHK$, while that of the public is estimated as 17.97 t/mHK$ by using $e^{ln(WGR)}$ (see Table 3).

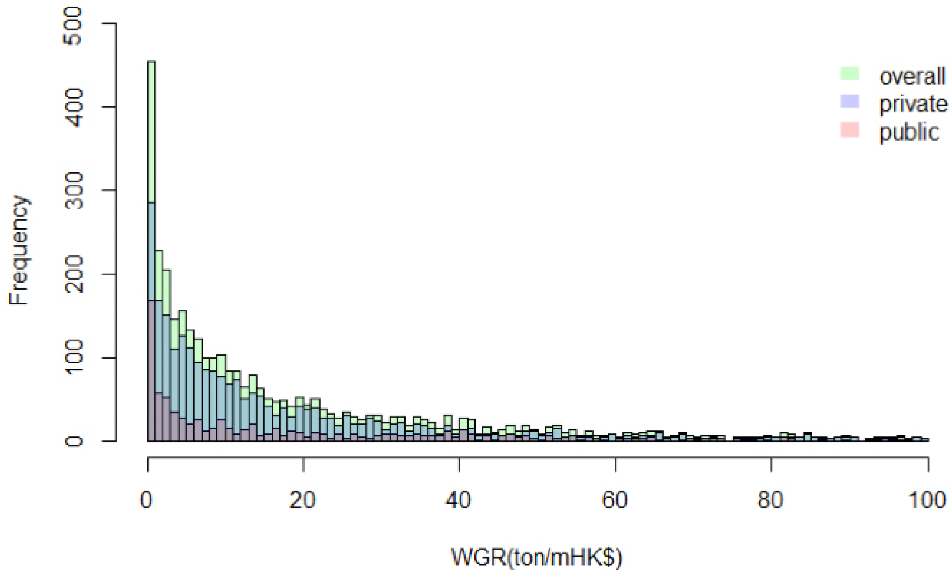


Fig. 7 Histogram of WGRs of overall, private, and public projects

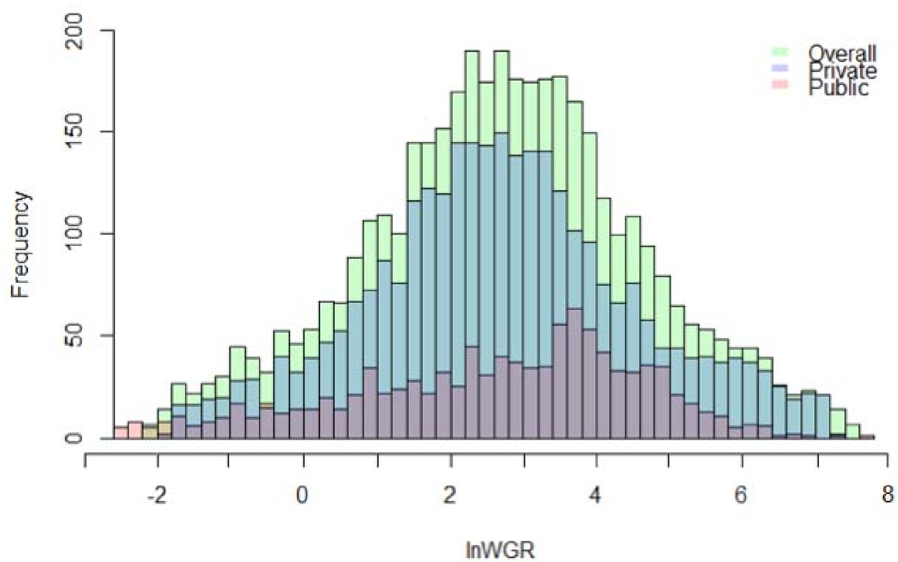


Fig. 8 Histogram of *ln(WGR)*s of overall, private, and public projects

Table 3 Means, medians of WGRs and standard deviations (SD) of private and public projects

Project	Sample size (*N*)	Mean of WGRs	Standard Deviation (SD)	Median of WGRs (t/mHK$)
Private	3,133	75.48	179.49	14.31
Public	1,084	53.26	117.47	17.97

One notable result is the large disparity between the means of WGRs and medians of WGRs as derived from both private and public projects. When it is a normal distribution, mean is median, and it is legitimate to use mean as a measure of the average value of a sample. However, simply using means without considering the distribution of the sample could be very misleading to understand average CWM performance, as evidenced by the large disparity between the two (see Table 3). Another notable result is that, without the big data to allow for a comprehensive examination of a large number of projects over a relatively long period (two years in this case), the resulting WGRs could also be very misleading for understanding average CWM performance. An empirical study, if measuring WGRs only in a limited number of projects in a confined area cordoned off, or in a short period of time (i.e. examining a very limited number of histograms in Fig. 7), is inherently limited by its failure to account for other truths or a totality of truth. In contrast, using the big data and robust statistical methods, it is sufficient to examine all the projects and derive a more reliable average WGR. In this study, the median, 14.31 t/mHK$ describes the WGR level of private projects, and 17.97 t/mHK$ reflects that of public projects. Judging from this, it is evident that the private sector is doing better than its public counterpart in managing C&D waste. Hypothesis H_1 is thus denied.

Inert and non-inert WGRs of private and public projects by production sectors

It could be argued that the foregoing analyses is over simplified since the two sectors have different project profiles that will generate different amounts of inert and non-inert construction waste, which is considered by existing CWM systems as having different impacts on the environment, landfills and public fill space. In light of this contention, the data was subsequently examined in greater detail. Fig. 9 and Fig. 10 are the distributions of natural logarithms of non-inert and inert WGRs, i.e. $ln(WGR_{non\text{-}inert})$ and $ln(WGR_{inert})$ for each type of projects, namely, (a) building, (b) civil, (c) demolition, (d) foundation, (e) M&R, and (f) others. These distributions are either Normal Distributions or similar. Therefore, medians instead of means are used to estimate the average CWM performance of each type of projects. Mood's median, as a non-parametric test, is used to test the equality of medians from two or more populations. If the *p*-value of Mood's median test is small, the two populations have a significant distinction in terms of their medians. Usually, a *p*-value of 0.05 is used as the criterion of significance in Mood's test. The test results are shown in Tables 4 and 5.

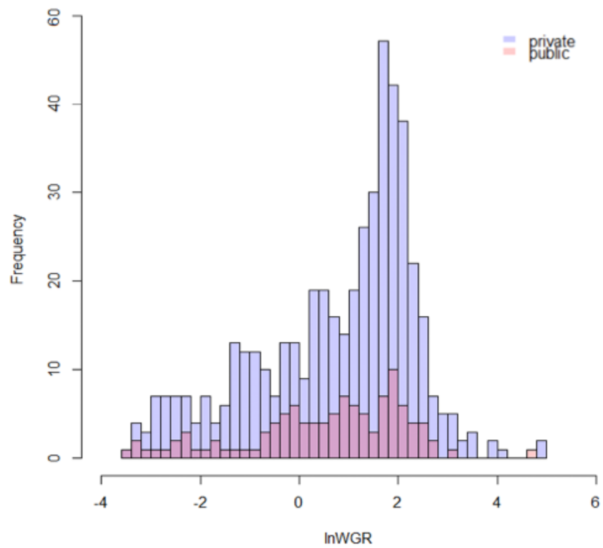


Fig. 9 (a) Distribution of *ln(WGR$_{non\text{-}inert}$)*s of private and public building projects

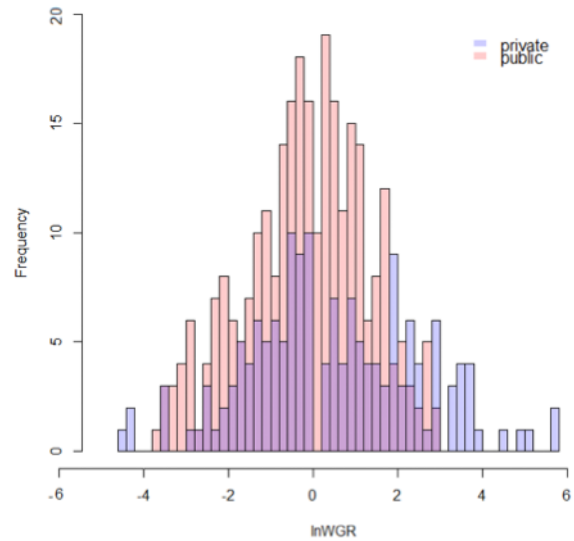


Fig. 9 (b) Distribution of *ln(WGR$_{non\text{-}inert}$)*s of private and public civil projects

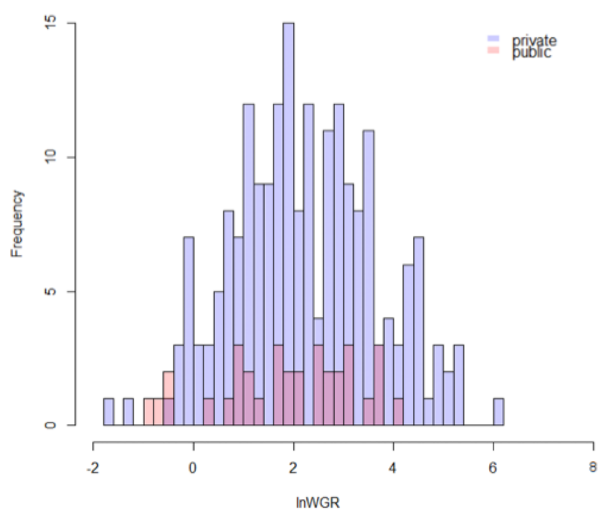


Fig. 9 (c) Distribution of *ln(WGR$_{non\text{-}inert}$)*s of private and public demolition projects

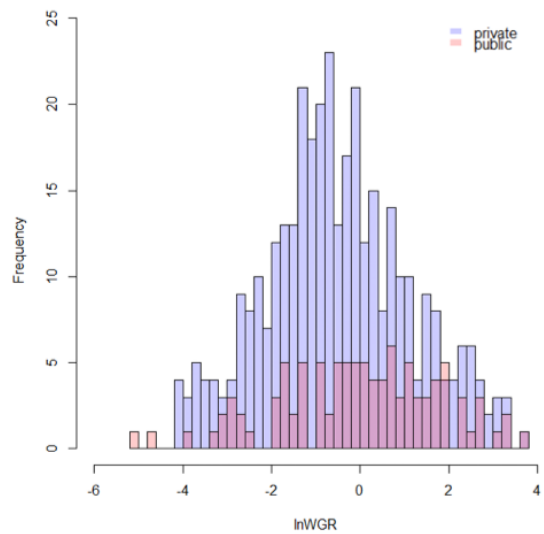


Fig. 9 (d) Distribution of *ln(WGR$_{non\text{-}inert}$)*s of private and public foundation projects

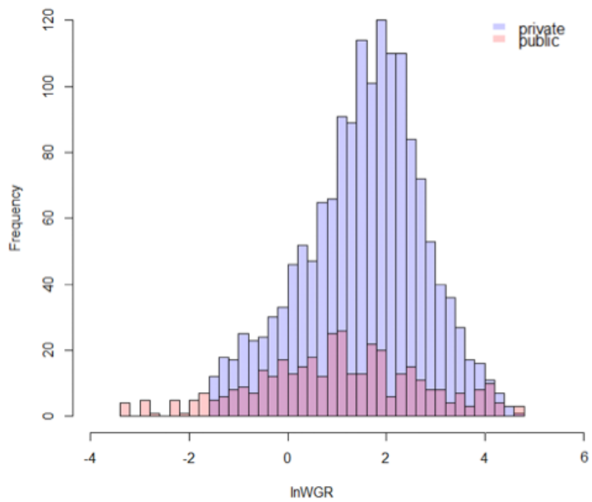


Fig. 9 (e) Distribution of *ln($WGR_{non\text{-}inert}$)*s of private and public M&R projects

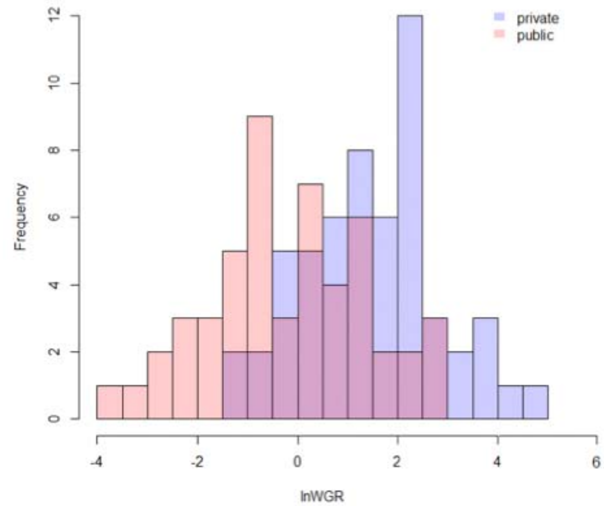


Fig. 9 (f) Distribution of *ln($WGR_{non\text{-}inert}$)*s of private and public other projects

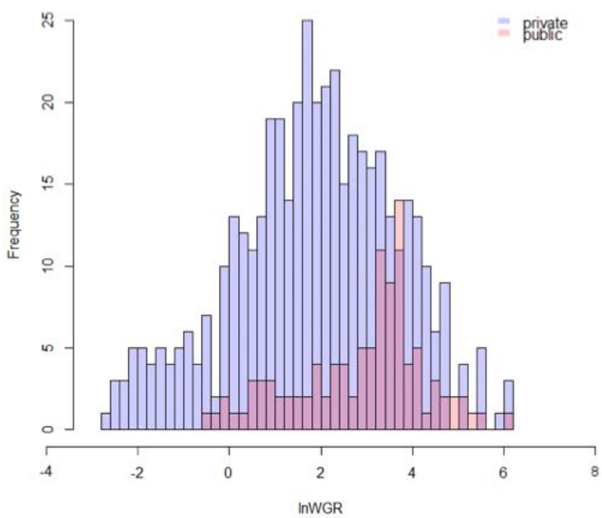


Fig. 10 (a) Distribution of *ln(WGR_{inert})*s of private and public building projects

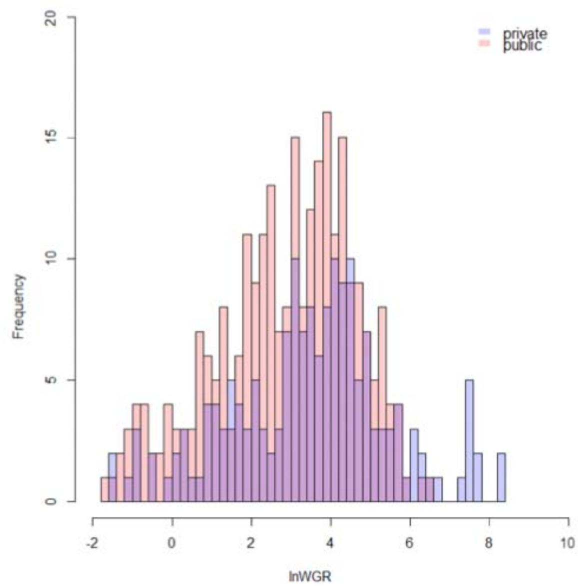


Fig. 10 (b) Distribution of *ln(WGR_{inert})*s of private and public civil projects

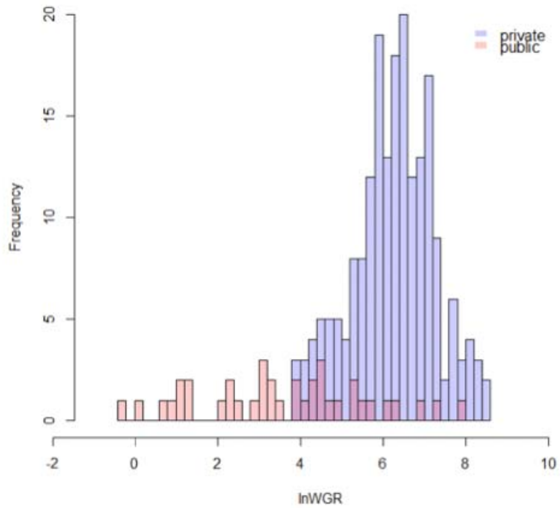


Fig. 10 (c) Distribution of $ln(WGR_{inert})$s of private and public demolition projects

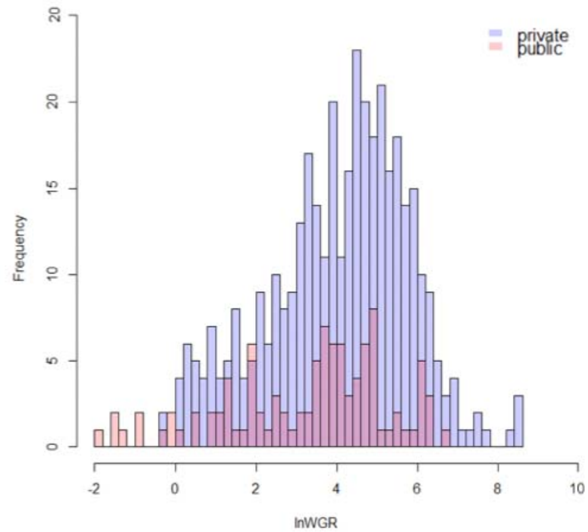


Fig. 10 (d) Distribution of $ln(WGR_{inert})$s of private and public foundation projects

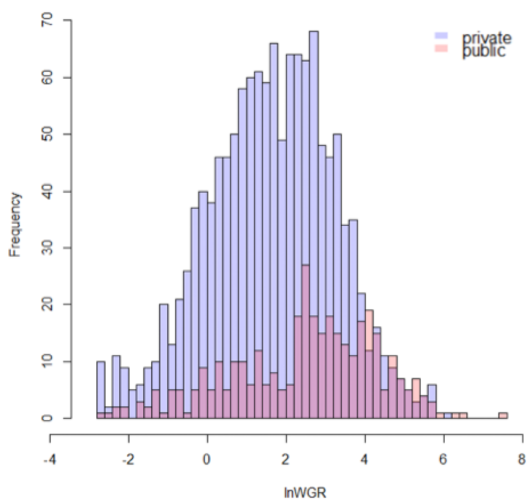


Fig. 10 (e) Distribution of $ln(WGR_{inert})$s of private and public M&R projects

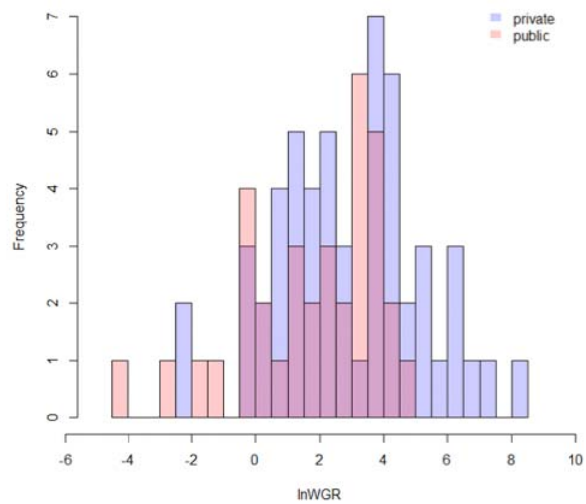


Fig. 10 (f) Distribution of $ln(WGR_{inert})$s of private and public other projects

Table 4 Comparison of non-inert WGRs between private and public projects

Projects	Median WGR (t/mHK$)		Median difference (private-public)	Mood's test	
	Private	Public		*p*-value	Significant difference? (Y/N)
Building	3.50	2.30	1.20	0.02	Y
Civil	1.46	0.90	0.55	0.20	N
Demolition	8.30	7.47	0.82	1.00	N
Foundation	0.54	1.14	-0.60	0.00	Y
M&R	5.29	2.77	2.53	0.00	Y
Others	4.55	0.94	3.62	0.00	Y

As shown in Table 4, the public sector outperformed its private counterpart in managing non-inert C&D waste in almost all types of projects ($Median_{private}$-$Median_{public}$>0, the larger the median, the worse of the CWM performance) except for foundation works, although statistically there is no significant performance difference between the public and private sectors in managing non-inert C&D waste from civil and demolition works. This seems contradictory to the results above, which revealed that overall the private sector is performing better than their public counterpart in managing C&D waste.

Bearing in mind that inert C&D waste takes a large proportion of the total construction waste, this research further examines the performance disparity of managing inert waste between the two sectors. Table 5 shows that again the public sector outperformed the private sector in managing inert construction waste from civil, demolition, foundation, and other works ($Median_{private}$-$Median_{public}$>0) but not so in building and M&R works ($Median_{private}$-$Median_{public}$<0). By interpreting the WGRs in Tables 4 and 5 in conjunction with the project profiles in Table 2, it can be seen that the private sector performed better in the large volume of building and M&R works, which consequently skewed the total sample and led to the conclusion that overall the private sector performed better than the public sector in managing C&D waste. Once again, Hypothesis H1 is unsupported.

Table 5 Comparison of inert WGRs between private and public projects

Projects	Median WGR (t/mHK$)		Median difference (private-public)	Mood's test	
	Private	Public		*p*-value	Significant difference? (Y/N)
Building	6.84	27.47	-20.63	0.00	Y
Civil	36.87	21.32	15.55	0.01	Y
Demolition	546.15	39.36	506.79	0.00	Y
Foundation	79.08	40.41	38.67	0.03	Y
M&R	5.31	15.25	-9.94	0.00	Y
Others	15.89	10.65	5.24	0.40	N

Based on the detailed analyses of the big data, the full story is that: (1) there is a notable CWM performance disparity between the public and private sectors; (2) overall, the private sector performed better in managing C&D waste; (3) contractors' CWM performance is better in conducting the large volume of private building and M&R works; and (4) contractors tend to perform better in managing both inert and non-inert waste when they undertake other types of public projects.

Discussion

Previous studies have reported that the behavior of contractors in Hong Kong changes in line with CWM public policies, particularly after implementation of the CWDCS (Lu, 2013b; Lu and Tam, 2013). For example, to save waste disposal levies, contractors paid more attention to construction waste reduction, reuse, and recycling (3R) before the residual waste is unavoidably disposed of at landfills (Hao et al., 2008). Construction waste is often a mixture of inert and non-inert material, although it is advisable to segregate the two and send them to different destinations instead of disposing them of as a whole. Poon et al. (2001) found that construction contractors were reluctant to carry out on-site waste sorting, in spite of the perceived advantages of doing so. By taking Poon et al.'s (2001) study as a point of departure, Yuan et al. (2013) reported contractors' change of behavior in relation to on-site sorting. Owing to the confined construction sites and/or high labor costs, contractors may send a mixture of inert and non-inert construction waste to offsite sorting facilities that charge less than the cost of disposing of it at landfills (Lu and Yuan, 2012).

Based on the analyses of the set of secondary big data, it is intriguing to discover that the same pool of contractors performed differently in CWM after they entered into different contractor-client relationships. It is against orthodox wisdom that contractors should behave the same under the same set of CWM public policies. However, the Coase Invariant Theorem can explain the performance disparity. The disparity is a result of different resource allocations that is caused by higher social scrutiny and closer monitoring. Probably owing to the widespread awareness of the impact of non-inert waste on the environment and valuable landfills, contractors deliberately allocate resources to deal with it. Therefore, the absolute difference between the two sectors is not great (see Table 4). This performance disparity is also observed in managing inert construction waste. One of the interviewees, who is a contractor, reflected that public projects receive higher social scrutiny in construction waste management. These public projects should show leadership in environmental management. Yet, in private projects, efficiency of materializing the physical project is the business mantra. While this is by no means something that should be criticized in a commercial society like Hong Kong, contractors generally pay less attention to CWM, which compete for resources against the main trades in materializing the project. Certain forms of institutions would improve CWM performance, although both the private and public sectors are under the same set of public policy CWM regulations.

CWM, which is viewed as a production function, involves not only production costs (e.g. the labor allocated to the 3Rs) but also various kinds of transaction costs. Voice from the industry complained that the current CWDCS has not considered the heavy transportation cost to transport the waste from a site to the government facilities; the cost per trip could be higher than the waste disposal levy itself. Enforcement of policies for encouraging better CWM performance has never been costless. An enhanced trip-ticket system (TTS) is used to ensure that all construction waste generated by public construction works is properly disposed of through tracking the waste destination (Lu and Yuan, 2012). Even with this enhanced TTS, there are allegations of illegal dumping, i.e. dumping construction waste in undesignated places so as to avoid the waste disposal levies. The illegal dumping of waste has been a serious environmental concern (Ichinose and Yamamoto, 2011). To better monitor potential illegal dumping, HKHA, as the government public housing developer, is working with Hong Kong Construction Industry Council (CIC) to tag all lorries with tracking technologies (e.g. Radio Frequency Identification and Global Positioning System). The interviewees in this study implied that the public sector has less incentive to be involved in illegal dumping.

Another example of how transaction cost impacts CWM performance can be seen from the performance disparity of managing demolition and foundation works between the private and public sectors (see Table 5). Public clients have a large pool of projects, which allow some of the ICW generated from one project to be reused in another (e.g. for backfilling). Conversely, private clients, as various individual profit centers, have higher cost to search for the ICW demand and supply information. More often than not, they just simply transport the ICW to government waste reception facilities without adequately considering other options.

With all the potential production and transaction costs numerated, they still take only a small portion of the overall cost of materializing a construction project. Conscious minimization of construction waste so as to save waste disposal levies is rarely high on a contractor's agenda, particularly in Hong Kong where projects often have a very tight schedule. It is not the intention of this research to suggest increasing waste disposal levies, although the stakeholders of CWM in Hong Kong is seriously considering this option. Instead, findings from the analyses suggest that with non-zero transaction cost, some slightly different 'assignment of rights and liabilities' (e.g. closer social scrutiny and monitoring of contractors) could significantly impact CWM performance, even though both the public and private sectors are subject to the same laws and regulations.

Conclusion

Through a thorough examination of the waste disposal records 4,227 sizable construction projects in Hong Kong over a period of two years, it is discovered there is a notable disparity of construction waste management (CWM) performance between the public and private sectors. This is against orthodox wisdom that contractors should behave the same under the same set of CWM public policies regardless of the sector that employs them. However, this can be explained by the Coase Invariant Theorem, which asserts that certain forms of institution would influence CWM performance by changing transaction costs even though both sectors are subject to the same set of formal public policies. It is revealed in this study that clients' strive to be environmental protection leaders, and consequently monitor their contractors' CWM practices closely, which clearly makes a significant difference to contractors' CWM performance. This research thus provides meaningful insights into CWM policy-making by finding that more attention needs to be paid to latent institutional arrangements in order to improve the effectiveness of public policies. Exploring tailor-made public policies that can further enhance CWM performance in both the public and private sectors are thus highly recommended for future research.

Big data showed its strength in this research by providing a fuller picture, based on which a closer claim on the objective truth can been made; which is, overall contractors tend to perform better in managing construction waste when they undertake private sector projects. They particularly perform better in managing waste generated from private building, and maintenance and renovation works but no so evident in other types of public projects. Big data research in CWM is still in its infancy with many challenges ahead, two of which are how to derive secondary, objective big data, and how to process it to mine latent knowledge or 'actionable information' using more robust approaches. It is, however, envisaged that more CWM studies using big data will be undertaken in the future given the booming data processing technologies around the world.

Acknowledgements

The National Nature Science Foundation of China (NSFC) supported the research (project no.: 71273219).

References

ACE (Advisory Council on The Environment), 2007. Progress Report on Construction Waste Disposal Charging Scheme. ACE Paper 9/2007. Available at: goo.gl/rX6fCS. Accessed on 3/4/2015.

Agrawal, A., 2006. Engaging the inventor: exploring licensing strategies for university inventions and the role of latent knowledge Source. Strategic Management Journal 27 (1), 63 -79.

Akintoye, A., Hardcastle, C., Beck, M., Chinyio, E., Asenova, D., 2003. Achieving best value in private finance initiative project procurement. Construction Management and Economics 21 (5), 461-470.

Arthur, L., 2013. Big data marketing: engage your customers more effectively and drive value. John Wiley & Sons, Hoboken, New Jersey, United States.

Boiral, O., Henri J.F., 2012. Modelling the impact of ISO 14001 on environmental performance: A comparative approach. Journal of Environmental Management 99, 84–97.

Bossink, B.A.G., Brouwers, H.J.H., 1996. Construction waste: quantification and source evaluation. Journal of Construction Engineering and Management ASCE 122 (1), 55–60.

Cappucio, D., 2010. Infrastructure & operations: Top 10 trends to watch. Gartner. Paper presented at the Gartner Symposium Conference, Cannes, France, October 2010.

Cheung, S.N.S., 1991. On the new institutional economics. Paper presented at the Nobel Prize in

Economic Science Presentation Ceremony, Stockholm, Sweden.
Clifton, C., 2010. Encyclopedia britannica: definition of data mining. Retrieved on 09/12/2010.
Coelho, A, de Brito, J., 2012. Influence of construction and demolition waste management on the environmental impact of buildings. Waste Management 32, 532–41.
Dahlbo, H., Bachér, J., Lähtinen, K., Jouttijärvi, T., Suoheimo, P., Mattila, T., ... Saramäki, K., 2015. Construction and demolition waste management–a holistic evaluation of environmental performance. Journal of Cleaner Production, doi:10.1016/j.jclepro.2015.02.073.
Fayyad, U.M., 1996. Data mining and knowledge discovery: Making sense out of data. IEEE Intelligent Systems 11 (5), 20-25.
Formoso, T.C., Soibelman, M.L., Cesare, C.D., Isatto, E.L., 2002. Material waste in building industry: main causes and prevention. Journal of Construction Engineering and Management ASCE 128 (4), 316–325.
Friedman, M., Friedman, R., 1990. Free to Choose: A Personal Statement. Houghton Mifflin Harcourt, United States.
Hao, J.L., Hills, M.J., Huang, T., 2007. A simulation model using system dynamic method for construction and demolition waste management in Hong Kong. Construction Innovation: Information, Process, Management 7 (1), 7-21.
Hillebrandt, P.M., 1974. Economic theory and the construction industry. London: Macmillan.
Ichinose, D., Yamamoto, M., 2011. On the relationship between the provision of waste management service and illegal dumping. Resource and Energy Economics 33 (1), 79-93.
Kantardzic, M., 2003. Data Mining: Concepts, Models, Methods, and Algorithms, John Wiley & Sons, Hoboken, New Jersey, United States.
Katz, A., Baum, H., 2011. A novel methodology to estimate the evolution of construction waste in construction sites. Waste management 31 (2), 353-358.
Kofoworola, O.F., Gheewala, S.H., 2009. Estimation of construction waste generation and management in Thailand. Waste management, 29 (2), 731-738.
Lai, L.W.C., Ngar Ng, F.W., Yung, P. (2008). The Coase Theorem and a Coasian construction economics and management research agenda 1. Construction Management and Economics 26 (1), 29-46.
Li, J., Ding, Z., Mi, X., Wang, J., 2013. A model for estimating construction waste generation index for building project in China. Resources, Conservation and Recycling 74, 20– 26.
Lu, W.S., 2013a. Beyond the inert and non-inert dichotomy: towards 'building a zero waste Hong Kong'. Building Journal 13, 46-49.
Lu, W.S., 2013b. Construction waste - Hong Kong style. Waste Management World, www.waste-management-world.com/articles/print/volume-14/issue-4/features/construction-waste-hong-kong-style.html accessed on 30/09/2014.

Lu, W.S., Tam, V.W.Y., 2013. Construction waste management policies and their effectiveness in Hong Kong: A longitudinal review. Renewable and Sustainable Energy Reviews 23 (2013) 214–223.

Lu, W.S., Tam, V.W.Y., 2014. Construction waste management profiles, practices and performance: a cross-jurisdictional analysis in four countries. ASCE Journal of Professional Issue in Engineering Practices, In Reviewing.

Lu, W.S., Yuan, H., 2011. A framework for understanding waste management studies in construction. Waste Management 31 (6), 1252-1260.

Lu, W.S., Yuan, H., 2012. Off-site sorting of construction waste: what can we learn from Hong Kong? Resources, Conservation and Recycling 69, 100– 108.

Lu, W.S., Yuan, H., Li, J., Hao, J., Mi, X., Ding, Z., 2011. An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. Waste Management 31(4), 680-687.

McGregor, M., Washburn, H., Palermini, D., 1993. Characterization of Construction Site Waste: Final Report. Presented to the METRO Solid Waste Department, Portland, Oregon.

Poon, C.S., Yu, A.T.W., Ng, L.H., 2001. On-site sorting of construction and demolition waste in Hong Kong. Resources, Conservation and Recycling 32 (2), 157-172.

Poon, C.S., Yu, A.T.W., Wong, S.W., Cheung, E., 2004. Management of construction waste in public housing projects in Hong Kong. Construction Management and Economics 22 (7), 675–689.

Poon, C.S., Yu, A., Wong, A., Yip, R., 2013. Quantifying the Impact of Construction Waste Charging Scheme on Construction Waste Management in Hong Kong. Journal of Construction Engineering and Management ASCE 139 (5), 466–479.

R Development Core Team, 2008. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org, accessed on 29/08/2014

Ramzy, A., 2013. China's Mountains of Construction Rubble. Sinosphere. Retrieved from website: sinosphere.blogs.nytimes.com/2013/10/20/chinas-mountains-of-construction-rubble/?_r=0, accessed on 10/10/2014

Roche, T.D., Hegarty, S., 2006. Best practice guidelines on the preparation of waste management plans for construction and demolition projects.

Rodríguez, G., Medina, C., Alegre, F.J., Asensio, E., de Rojas, M.S., 2014. Assessment of C&DW plant management in Spain: in pursuit of sustainability and eco-efficiency. Journal of Cleaner Production, doi:10.1016/j.jclepro.2014.11.067.

Sen, P. K., Singer, J. M., 1993. Large sample methods in statistics. Chapman & Hall, Inc.

Shah, S., Horne, A., Capellá, J., 2012. Good data won't guarantee good decisions. Harvard Business Review 90 (4), 23-25.

Skoyles, E.R., 1976. Materials wastage – a misuse of resources. Building Research and Practice 232–243 (July/August 1976).

Stigler, G.J., 1987. The Theory of Price. 4th ed. New York: Macmillan.

Tam, V.W.Y., Tam, C.M., Zeng, S.X., Ng, W.C.Y., 2007. Towards adoption of prefabrication in construction. Building and Environment 42 (10), 3642–54.

The National Council for PPP, 2014. Retrieved from website: www.ncppp.org/ppp-basics/7-keys/, accessed on 10/10/2014.

Treloar, G.J., Gupta, H., Love, P.E, Nguyen, B., 2003. An analysis of factors influencing waste minimisation and use of recycled materials for the construction of residential buildings. Management of Environmental Quality: An International Journal 14 (1), 134-145.

WEF (World Economic Forum), 2012. Big data, big impact: new possibilities for international development. Available at: www3.weforum.org/docs/WEF_TC_MFS_BigDataBigImpact_Briefing_2012.pdf, accessed on 10/10/2014.

Xuan, D.X., Molenaar, A.A.A., Houben, L.J.M., 2015. Evaluation of cement treatment of reclaimed construction and demolition waste as road bases. Journal of Cleaner Production, doi:10.1016/j.jclepro.2015.03.033.

Yuan, H.P., 2013. A SWOT analysis of successful construction waste management. Journal of Cleaner Production 39, 1-8.

Yuan, H.P., Lu, W.S., Hao, J.L., 2013. The evolution of construction waste sorting on-site. Renewable & Sustainable Energy Reviews 20, 483-490.