Revisiting the effects of prefabrication on construction waste minimization: a quantitative study using bigger data

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Highlights

- Exploit quantitative dataset of 114 high-rise building projects in Hong Kong
- Re-evaluate the effects of prefabrication on construction waste minimization
- Reconfirm the positive effects of prefabrication on construction waste minimization
- Two types of precast components played bigger roles in waste minimization

Abstract

Prefabrication has long been recognized as a green production technology to minimize construction's adverse environmental impacts such as waste, noise, dust, and air pollution. Previous studies reported the effects of prefabrication on construction waste minimization. However, these studies relied primarily on small data obtained by ethnographic methods such as interviews and questionnaire surveys. Research to evaluate the effects using bigger, more objective quantitative data is highly desired. This research aims to re-evaluate the effects of prefabrication on construction waste minimization by exploiting a quantitative dataset stemmed from 114 sizable high-rise building projects in Hong Kong. It was discovered that the average waste generation rates of conventional and prefabrication building projects were 0.91 and 0.77 ton/m^2 respectively. Compared with conventional construction, prefabrication logged a 15.38% waste reduction. Further probing into specific prefabricated components adopted in the samples, it is discovered that precast windows and walls are more conducive to waste minimization. This is coincident with the fact that these components are also widely adopted in the sample buildings. This study reconfirms the positive effects of prefabrication on waste minimization and articulates that two types of prefabricated components play relatively bigger role in minimizing construction waste. The strengths of this study lie in its statistical analyses of a valuable and objective quantitative dataset measuring prefabrication and waste generation rates. Future studies are recommended to prove the corollary - it is not what category of prefabricated component, but the actual proportion of prefabrication in the total construction volume that matters to waste minimization.

Keywords: Construction waste management; Waste minimization; Prefabrication; Big data analytics; Hong Kong

1. Introduction

Construction waste, sometimes called construction and demolition (C&D) waste, means the solid waste generated from construction activities such as site clearance, excavation, construction, refurbishment, renovation, demolition, and road works (USEPA, 2020; Lu et al., 2019). It mainly contains waste construction materials such as debris, rubble, earth, soil, broken concrete, bamboo, timber, vegetation, packaging waste, and others (HKEPD, 2020). Of the overall construction waste generated, the non-inert portion takes around 5%, but this small portion often occupies around 25-30% of all the solid waste landfilled. Landfilling not only takes up precious landfill space but also causes severe environmental problems due to the production of greenhouse gases such as CO_2 and methane (Wu et al., 2019a), as well as leachate from anaerobic degradation of the waste. Hence, construction waste minimization (CWM), e.g., via reuse, rethink, replace, reduce, refuse, and recycle (a.k.a., “6R”) (Boon and Anuga, 2020), is always high on the governments' agenda. CWM is also one of the main areas to rebuild a circular economy (Esa et al., 2016), which aims at extracting the maximum value from resources and minimizing pollution and end-of-life waste.

Prefabrication has long been advocated as a green production strategy to alleviate the negative environmental impacts caused by construction. "Prefabrication", as opposed to "cast in-situ" construction, is the practice of assembling components of a structure in a factory or other manufacturing site, and transporting complete assemblies or sub-assemblies to the construction site where the structure is located (Beecher, 2014). Some prefer to use "offsite construction", which refers to sub-structures or components of a structure built at an offsite place other than the location of final erection (Gibb, 1999). For example, individual modules of the building are constructed in an offsite place (e.g., a factory or a precast yard) then transported to the site for assembling to a final building. Other terms such as "precast", "industrialized construction", or "construction industrialization", are also seen. A detailed account of the similarities and subtle differences among the concepts will be given later. Prefabrication allows many traditional "cast in-situ" trades to be conducted in a factory environment. Therefore, it is amenable to CWM, e.g., by reducing material waste (Lu and Yuan, 2013), losses or misplacements of materials (Tam et al., 2005), or the impact from the weather (Wuni and Shen, 2019).

Research to quantify the effects of prefabrication on CWM is hardly new. Tam et al. (2007), for example, conducted one of the earliest studies in Hong Kong and found that "wastage generation can reduce up to 100% after adopting prefabrication". Jaillon and Poon (2009) conducted a comprehensive review of the evolution of prefabricated residential building systems in Hong Kong. Using questionnaire surveys and case studies, Jaillon et al. (2009)

discovered that CWM is one of the major benefits when using prefabrication construction; "the average wastage reduction level was about 52%". Tam and Hao (2014) found that the use of prefabricated components could reduce timber formwork waste and concrete waste by up to 86.67% and 60%, respectively. Lu and Yuan (2013) discovered that "the waste generation rate in the upstream processes of offshore prefabrication is around 2% or lower by weight". Osman and Lee (2016) conducted a questionnaire survey and found that 74% of the 300 respondents agreed that prefabrication effectively reduced construction waste, especially timber formwork waste. Eghbali et al. (2019) investigated waste generation levels of 17 projects and discovered that prefabrication could reduce 40% to 100% of waste. Nevertheless, one common shortcoming of these studies is that they deployed small and erratic data collected using ethnographic methods such as interviews, questionnaires, or observations. Such small and erratic data may only reflect a snapshot of waste generation in a project. Hence, using bigger, more thorough, and more objective data to examine the dyadics, i.e., prefabrication and CWM, is highly desirable in literature, policy making, and construction practices.

This study aims to re-evaluate the effects of prefabrication on CWM. It does so by making good use of a big dataset collected from 114 large-scale high-rise building projects in Hong Kong, including their categories of prefabricated components adopted and factual waste generation. The remainder of this paper is structured as follows. Following this introductory section is a literature review of prefabrication construction with particular focus on the current status of prefabrication adoption in high-rise buildings, as well as an evaluation of its potential in CWM. Section 3 is the methodology which describes the data used and analytical methods employed, including cross-sectional comparison and correlation analyses. Section 4 reports the results and findings of cross-sectional analysis by way of independent samples t-test, Spearman correlation analyses, and comparison of the average waste generation rates (WGRs) of projects with varying estimated levels of usage of different categories of prefabricated components. Section 5 is an in-depth discussion, followed by the strengths and limitations of this study highlighted in Section 6. Finally, conclusions are drawn in Section 7.

2. Literature review

2.1 Prefabrication for high-rise building construction

Prefabrication represents a construction approach that is different from the traditional "cast in-situ", where formwork is set up onsite for pre-mixed concrete to be cast in. The concrete then needs to undergo a process of "hardening" in the formworks supported by falsework, which normally takes a few weeks before it becomes a self-standing and permanent structure (Kwan and Ling, 2015). Cast in-situ construction is predominantly of wet trades onsite (e.g., tilelaying, bricklaying, concreting, and plastering), which cause much nuisance, including construction waste. There are many other similar terms related to the concept of "prefabrication". For example, "precast" is a construction product (mostly concrete) produced by casting concrete in a reusable "mold" or "form", which is then cured in a controlled environment and transported to the construction site for lifting to its final position (Chea et al., 2020). "Industrialization" refers to the extensive use of large-sized factory-finished elements and the conversion of production into a mechanized and continuously flowing process of assembly and installation of buildings and structures made of prefabricated assemblies and parts (Rostami et al., 2013). Nevertheless, it should be noticed that these concepts are not mutually exclusive with one other. Instead, they emphasize different aspects of prefabrication. For example, not all prefabrication must be offsite; there are also onsite prefabrication works, particularly for road or bridge projects. With prefabrication conducted in an offsite place, it is possible to realize construction industrialization. In this paper, these terms are aligned into one, i.e., "prefabrication", but readers are reminded of their subtle differences.

Over the years, prefabrication has not only been used in low-rise, detached or semi-detached houses, but also been adopted in high-rise building projects in metropolitan cities such as New York, Tokyo, Singapore, Hong Kong, and many other densely populated places. Steel, with its strong compress and tensile strengths and the ability for free extension (Chukin et al., 2010; Zhang et al., 2019), is a perfect material for prefabrication in high-rise buildings. The drawback is the high cost (Wu et al., 2010) and poor fire-resistance, as we learned from the tragedy of "911" (Bement, 2002; Shuster, 2005). Therefore, on many occasions, full steel prefabricated structures are replaced by composite structures using concrete and steel materials. The composite structures have slightly inferior yet still acceptable structural properties, but possess the strengths of much lower costs and superior fire resistance.

Being a densely populated compact city with limited land, Hong Kong has long been employing offsite prefabrication, particularly in its massive public housing schemes. Around half of the city's housing units are public housing, which has a long history of adopting prefabrication, in one way or another (Ying, 2019). Figure 1 illustrates a typical floor of a public rental housing (PRH) block in Hong Kong constructed with prefabrication technology. The technology was historically considered as less stiff, less sound- and water-proof than cast in-situ construction (Hao et al., 2020). Therefore, it is not uncommon that the structural parts are still using the traditional construction while the precast components are manufactured beforehand and installed into the positions on the main structure.

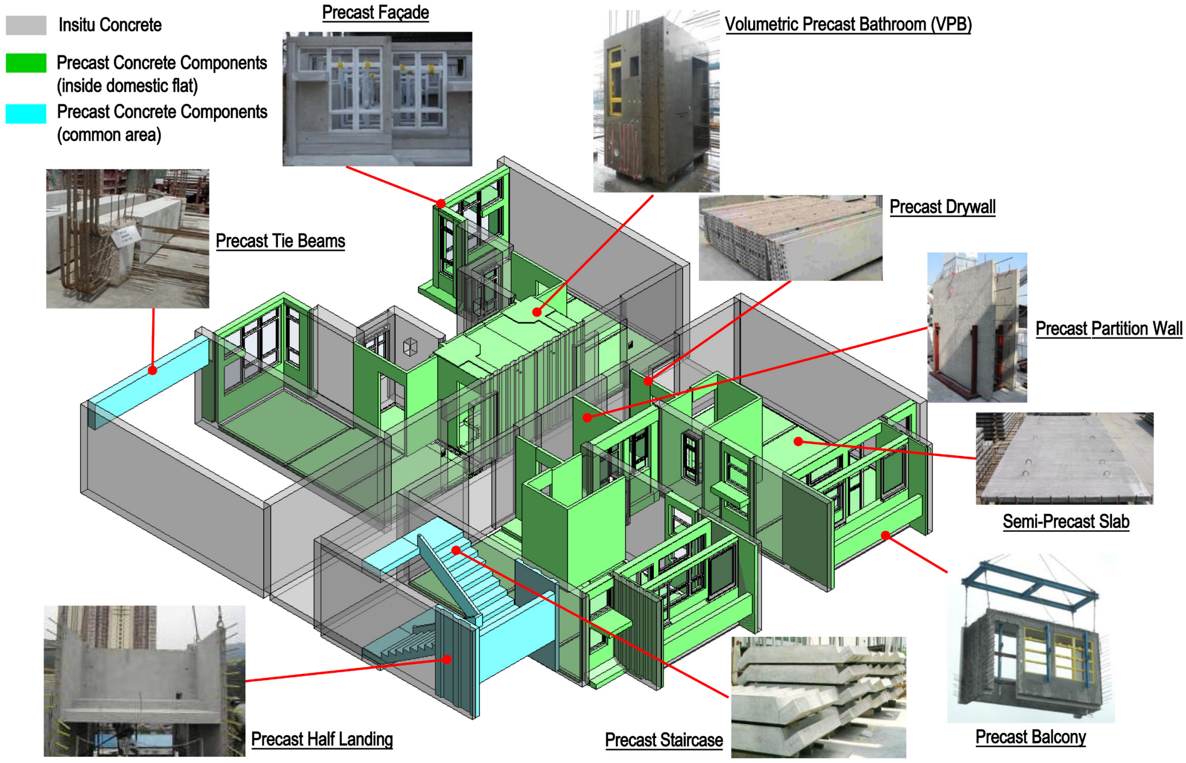

Figure 1. Typical floor of a PRH block in Hong Kong constructed with prefabrication technology (Source: HKHA, 2018)

An important footnote to understand prefabrication's effects on CWM is the level of prefabrication. It would form a misconception if considering that construction will adopt either cast in-situ or prefabrication. Actually, there are different levels of prefabrication adopted, ranging from full cast in-situ to complete prefabrication. An index-style measurement could offer a clear understanding of the proportion of prefabrication in the overall construction volume. Alinaitwe et al. (2006), for example, suggested that the level of prefabrication could be measured by the ratio of the value of work done onsite to offsite. Hong et al. (2016) proposed a "prefabrication rate" that is derived from the adopted prefabrication volume over the total construction volume. Gibb (1999) provides one of the most widely used approaches to measuring prefabrication levels (see Table 1). Using this taxonomy, the PRH in Hong Kong adopts a Level 2 prefabrication, and some of the projects adopted a Level 3 prefabrication. The city is enthusiastically advocating Modular Integrated Construction (MiC), which can be considered as Level 4 in Gibb's (1999) taxonomy.

Table 1. Taxonomy of different levels of prefabrication

Level	Description	Examples
0	Cast in-situ	Conventional construction technologies, using formwork and falsework, rebar and cast in premixed concrete
1	Component and sub-assembly	Components like doorsteps, lintels, and so on, to be formed as functional components such as doors and windows
2	Non-volumetric assembly	2-dimensional precast concrete wall panels, precast components with no usage space enclosed, e.g., precast concrete partition wall, precast lost form, semi-precast slab, non-structural prefabricated external wall
3	Volumetric assembly	Encompassing all 3D preassembled units enclosing usable space but do not constitute part of the building structure, e.g., volumetric precast bathroom, precast kitchen, precast water tank, precast refuse chute
4	Modular building	3D preassembled volumetric units forming part of or the complete building structure, like motel rooms, MiC

Source: Gibb (1999) and others.

2.2 Prefabrication as a key player in CWM

Adoption of prefabrication is one of the key contributors to CWM (Lu and Yuan, 2013; Wang et al., 2015; Ajayi et al., 2017). There are several explanations. Firstly, prefabrication construction minimizes the reliance on traditional wet trades (Poon et al., 2004). Secondly, the use of prefabricated components reduces the amount of waste resulting from negligent handling. Since conventional building materials are often unpacked during transportation, incidents of fragile materials being damaged, which render them unfit for purpose, are rampant (Tam et al., 2005). Thirdly, prefabrication avoids possible wastage arising from over-ordering of materials. Over-ordering of readily-mixed concrete due to improper planning or ensuring sufficient buffers was found to be one of the major causes of construction waste (Wang et al., 2008; Tam and Hao, 2014). Fourthly, the use of precast components eliminates construction waste arising from poor workmanship and cutting of materials. In conventional construction, off-cuts from the cutting of materials such as steel bars, bricks, and blocks can easily end up as waste rather than being reused (Osmani et al., 2006; Nadoushani et al., 2016). There are also instances where the steel bars and bricks being cut are unfit for their purposes (Tam et al., 2005). Lastly, factory conditions for prefabrication avoid the impact of weather and other onsite exposure, thereby reducing the generation of construction waste (Tam et al., 2005).

Despite the benefits being discussed above, the decision as to which level of prefabrication should be adopted is also contingent on political, economic, social, and environmental factors (Lu et al., 2018). Governments around the globe have been promoting prefabrication akin to a political agenda. They offer economic incentives to developers in recognition of their projects' fulfillment of certain requirements of using precast components (Kamar et al., 2009; Li et al., 2017; Lu et al., 2018). Prefabrication often incurs higher setting-up and higher transportation costs, which must be offset by the possibility of mass production, i.e., "economy of scale" (Chen et al., 2010; Bildsten, 2011). Prefabrication requires skilled labor with expertise in the lifting and onsite assembly of precast components, such as connecting them with the in-situ ones (Chiang et al., 2006). Thus, prefabrication adoption can be hindered by the shortage of relevant skilled labor in the market. The implementation of precast construction can also be impeded by the lack of site space for the temporary storage of precast units (Azhar et al., 2013).

Most previous studies have reached the conclusion that prefabrication construction is effective for CWM. They adopted such methods as interviews, questionnaires, or observations to collect the first-hand data. Undoubtedly, interviews can elicit in-depth information from respondents (Milligan et al., 2005; Meyer et al., 2017), and questionnaire survey enables the gathering of data from a large sample within a short period at a relatively low cost (Reynolds and Sponaugle, 1982). Nonetheless, the accuracy and quality of data collected by such ethnographic methods might be hampered by respondents' possible memory lapses (Snijkers, 2002). The interview data may just reflect a generation impression or a snapshot of the waste saving by adopting prefabrication. In fact, both prefabrication construction and its waste generation are tangible and amenable to objective measurement. It will be more desirable to measure the effects of prefabrication on CWM using more comprehensive and more objective secondary data that naturally happens on site.

3. Methodology

Basically, the methodology adopted in this study is a typical comparative study. There are five steps included in the comparative study. The first three steps are about data: (1) sampling the building projects; (2) collecting the data related to construction waste generation; and (3) collecting the data related to prefabrication. The rest two steps analyze the data to find out (4) whether prefabrication makes any difference in terms of CWM performance amongst different clients and building types; and (5) which type(s) of prefabricated components contribute most to CWM, if there is any. They are elaborated in greater details below.

3.1 Project sampling

Firstly, sample projects were identified with the aid of a project database obtained from the Hong Kong Environmental Protection Department (HKEPD) comprising basic information (e.g., contract number, contract name, contract sum, site address) of all six prevailing types of construction projects (i.e., demolition, building, renovation, site formation, the foundation works, others). We selected 157 projects ("initial sample projects") from the database based on four criteria:

1. The project type was restricted to "building", as prefabrication is mainly adopted in building projects;
2. The projects must be commenced and completed in the period from 2006 to 2019, as that is the period our database straddles;
3. The projects must be relatively sizeable, e.g., contract sum > HK$ 100 million and GFA > 3,000 m², to allow steady CWM patterns to surface; and
4. The projects had credible sources of data.

Data cleansing was conducted to remove projects with incomplete data from the sample. As a result, 114 projects, including 85 prefabricated and 29 conventional ones, were ultimately chosen for further analysis. Table 2 lists the profiles of the building projects. There were:

(1) 85 prefabrication and 29 conventional projects;

(2) 30 public projects (all being prefabrication projects) and 84 private projects (including 55 prefabrication and 29 conventional projects); and

(3) 91 residential projects (including 81 prefabrication and 10 conventional projects) and 23 commercial projects (including 4 prefabrication and 19 conventional projects).

Table 2. Basic profiles of the 114 sample projects

Prefab.?	**By client**		**By nature of building**		**Subtotal**
	Public	**Private**	**Residential**	**Commercial**	
Yes	30	55	81	4	85
No	0	29	10	19	29
Subtotal	30	84	91	23	114

Then, basic information of the initial sample projects was compiled in the form of an excel spreadsheet. The contract number, contract name, site address, clients (e.g., public or private), contract sum, Construction/Gross Floor Area (CFA/GFA), and waste disposal account number were distilled from the project database and supplemented from various sources, e.g., sales brochures of private developments, official websites of contractors, developers and government departments, as well as other public documents. Notably, this research managed to secure the CFA/GFA information. According to Tam and Lu (2016), the WGR per GFA (unit = ton/m^2) is a more objective indicator than tons/$ of the contract sum, as floor area is an objective indicator while contract sum as the denominator can change in line with different material prices in different regions.

3.2 Waste generation data collection

The total amount of waste generated by each project was collected with the aid of the HKEPD's Waste Disposal database, which records every truckload of construction waste received by government waste disposal facilities. We obtained all the truckload records of individual projects to calculate the total construction waste generation from specific projects. Afterward, we also computed the WGR of each project, which is a widely recognized indicator of construction waste management performance of building projects. In this study, the WGR of each project was calculated by dividing the total amount of waste generated (in tons) by the GFA (in m^2) of the project (Formoso et al., 2002; Lu et al., 2016; Zheng et al., 2017). The lower the WGR, the higher the CWM performance.

3.3 Prefabrication data collection

The types of prefabricated components adopted in these projects were identified using various public sources. The prefabrication information collection and cleansing processes took the research team around eight months with assistance from several summer interns, who browsed the initial sample projects' structural and building plans via HeBROS and BRAVO. These are two online systems operated by the Hong Kong Housing Authority (HKHA) and the Buildings Department of the Hong Kong Government (HKBD), respectively to store drawings and other information of all the buildings in Hong Kong. Figure 2 is a screenshot of the data collected for waste generation and prefabrication adoption. It is an expansive spreadsheet containing detailed information about the projects and prefabricated components.

Proje Id	Contract No.	Account No.	Contract name*	Contract sum (HK$)	Site address#	Client+	Gross Floor Area (GFA) (m2)^	Total amount of waste generated (tons)	Prefabricated component used? (Y/N)	Precast façades (part of window system) (Y/N)	Precast staircases (Y/N)	Semi-precast slabs (Y/N)	Precast balconies (Y/N)	Precast partition wall (Y/N)	Precast lost form (Y/N)	Precast bathrooms (Y/N)	Precast beams (Y/N)
P1	20120141	7016997	A	542500380	A1	H	25318.42	58209.3	Y	Y	Y	Y	N	Y	N	N	Y
P2	20110039	7015648	B	2233000000	B1	H	171223.42	161018.77	Y	Y	Y	Y	N	Y	N	N	Y
P3	20120263	7017381	C	2580000000	C1	H	183003.09	118018.97	Y	Y	Y	Y	N	Y	N	Y	Y
P4	20110333	7016204	D	2105000000	D1	H	117992.4	347503.98	Y	Y	Y	Y	N	N	N	Y	Y
P5	20120095	7016593	E	1142800000	E1	H	85772.974	33566.87	Y	Y	Y	Y	N	Y	N	Y	Y
P6	20120096	7016758	F	1232468000	F1	H	120454.63	41119.79	Y	Y	Y	Y	N	Y	Y	Y	Y

Note: *, #, and + There are specific project names, site addresses, and client names, which are pseudonymized for protecting privacy
^ Including both domestic and non-domestic GFA

Figure 2. An excerpt of the dataset collected in this study

Then, the prevailing prefabricated components were grouped into eight categories, as listed in Table 3. It can be seen that buildings in Hong Kong have adopted a wide range of precast components, ranging from big, sophisticated precast facades, balcony, kitchen, and bay windows, to small, simple ones such as slabs and partitioning walls. Precast façades are the most popular components. Hong Kong has developed a good knowledge of precast façades by integrating windows, sinks, and washing benches, and left pipes and openings for utilities to fit in. They represent a high level of non-volumetric assembly (Level 2) of prefabrication. Non-structural prefabricated external walls are also widely adopted. 51 out of the 85 prefabrication projects have adopted non-structural prefabricated external walls. Precast partition walls, as non-structural members, are also widely adopted. Simple precast slabs are popular components in a building. Owning to the conservative attitudes towards prefabrication's strengths, sound- and water-proof, semi-precast slabs are more popular than full precast slabs. On the top of the semi-precast slab, they often add an extra layer of rebar and concrete using cast in-situ technology. It can also be seen from Table 3 that Level 3 prefabrication components such as volumetric bathroom and kitchen are also adopted, although they are not prevailing. The widespread use of water tanks, lost forms, window frames, and refuse chutes demonstrate that Hong Kong's building clients are endeavored to embrace prefabrication as much as possible.

Table 3. Eight categories of prevailing prefabricated components

Category of components				**Type of prefab. component**	**Num. of projects**		
Id	**Name**	**Abbr.**	**Range**		**Public**	**Private**	**Total**
1	Façade	Fac.	{0, 1}	Precast façade	30	49	79
2	Staircase	sta.	{0, 1}	Precast staircase	29	2	31
3	Beam	Beam	{0, 1}	Precast beam	29	0	29
4	Window	Win.	{0, 1, 2}	Precast bay window	4	23	27
				Precast window frame	0	10	10
5	Slab	Slab	{0, 1, ..., 4}	Semi-precast slab	21	3	24
				Full precast slab	14	0	14
				Precast plank	17	1	18
				Semi-precast plank	1	0	1
6	Wall	Wall	{0, 1, …, 7}	Precast partition wall	23	13	36
				Precast structural wall	0	1	1
				Semi-precast structural wall	2	0	2
				Non-structural prefabricated external wall	19	32	51
				Precast hanger wall	3	0	3
				Precast parapet wall	6	1	7
				Precast lost form	1	14	15
7	Volumetric	Vol.	{0, 1, …, 5}	Precast bathroom	8	0	8
				Precast kitchen	2	0	2
				Precast water tank	19	0	19
				Semi-precast water tank	3	0	3
				Precast refuse chute	15	0	15
8	Others	Oth.	{0, 1, …, 4}	Precast balcony	4	1	5
				Precast half-landing	7	0	7
				Semi-precast utility platform	0	1	0
				Miscellaneous types	–	–	–

One may notice that prefabrication has an unbalanced adoption in public and private projects. All public projects in the sample had adopted prefabrication, whereas only less than two-thirds of private projects had incorporated precast components. There are some drawbacks associated with prefabrication construction, e.g., higher cost, heavy transportation and hoisting, lack of flexibility, inadequate skillsets, and poor sound-/water-proof, some of which are true while others are stereotypical ideas. The Government, however, asserts that prefabrication is the direction to achieve a greener, safer, and more productive construction industry in Hong Kong, so it enacted various measures to boost prefabrication adoption. Particularly, prefabrication is recognized as one of the green features that can enjoy the exemption from GFA calculation pursuant to Joint Practice Notes No. 1 & 2 promulgated in 2001 and updated in 2019 (HKBD, 2019a and 2019b). This can increase the actual permissible GFA to be constructed and sold, thereby maximizing developers' monetary return. In contrast to public projects, which had incorporated a wide range of precast components covering both Levels 2 and 3 prefabrication, the private projects had employed a much narrower range of precast components, excluding any volumetric assemblies. Influential private sector clients, e.g., real estate developers in town, have found a delicate balance between enjoying the GFA exemption and maintaining their flexibility.

3.3 Analyzing the effects of prefabrication on CWM in different building types and clients

Cross-sectional comparison studies are performed to investigate the effect of prefabrication on CWM among different types of projects and clients. Basically, they encompass independent samples *t*-tests using the IBM SPSS (version 27). For comparing the effects measured by average WGRs, the 114 projects were grouped in the following ways in the *t*-tests:

(i) Prefabricated versus conventional projects
(ii) Prefabricated private versus conventional private projects
(iii) Prefabricated residential versus conventional residential projects
(iv) Prefabricated office versus conventional office projects

3.4 Analyzing the effects of different types of prefabrication on CWM

Firstly, Spearman correlation analyses are conducted to unravel the contributions of adopting different types of prefabricated components to CWM. A higher correlation coefficient means the use of such prefabricated components has a lower level of contribution to CWM (Sachs, 2012). In addition, independent samples *t*-tests are performed to explore whether there is any significant difference in the effect on CWM by adopting varying levels of precast window, slab, wall, and volumetric components.

4. Data analyses, results, and findings

4.1 Prefabrication's effect on CWM in different building types and clients

4.1.1 Cross-sectional comparisons between prefabrication and conventional buildings

The average WGRs and other statistics of such comparisons can be found in Table 4. The average WGRs of the prefabrication and conventional construction were 0.77 ton/m^2 and 0.91 ton/m^2, respectively. On an average scale, prefabrication construction reduced 15.38% waste generation. The results echo the findings of Jaillon et al. (2009) as well as Tam and Hao (2014), which reported that prefabrication could reduce the amount of waste generated. However, the 15.38% reduction was not statistically significant (p = 0.492 > 0.05), implying that other confounders such as project management, time, site, and technologies may also determine the CWM performance.

Table 4. Comparisons of CWM performance

Group by	Project type	Prefab.?	No. of projects	Average WGR (tons/m^2)			
				Mean	Stdev	Δ (%)	Significance#
Overall		Yes	85	0.77	0.86	-15.38	0.492
		No	29	0.91	1.10		
Client	Public	Yes	30	0.81	0.63	–	–
		No	0	–	–		
	Private	Yes	55	0.75	0.97	-17.58	0.497
		No	29	0.91	1.10		
Building nature	Residential	Yes	81	0.79	0.87	-15.05	0.633
		No	10	0.93	0.84		
	Commercial	Yes	4	0.43	0.64	-52.15	0.476
		No	19	0.90	1.24		

The p values of independent sample t-tests (Two-tailed)

4.1.2 Cross-sectional comparisons between client types

As listed in Table 4, there is no public project without adopting prefabrication. Therefore, to compare the effects of prefabrication on CWM against conventional construction is null. There are 55 and 29 private projects that adopted prefabrication and conventional construction respectively, and their average WGRs are 0.75 ton/m^2 and 0.91 ton/m^2 respectively, showing that prefabrication can reduce 17.58% waste generation. The difference was not statistically significant either (p = 0.497 > 0.05).

The results indicate that the private prefabrication projects had outperformed their counterparts in the public sector in CWM. The reason might be the private sector's predominant reliance on precast window and wall components, which were found to be the most effective in minimizing waste if they are widely adopted. Private clients also value the construction cost seriously. They will do enormous diligence to reduce material waste.

4.1.3 Cross-sectional comparisons among the nature of buildings

As listed in Table 4, both residential and commercial developments adopting prefabrication had considerably lower average WGRs than their conventional counterparts, with the percentage differences being 15.05% and 52.15%, respectively. Furthermore, the average WGR of residential prefabrication projects is over 80% greater than that of commercial developments with precast components. Amidst the low proportion of commercial projects incorporating precast components, commercial projects have exhibited a much greater reduction in average WGR compared with residential developments by only using precast wall and window components. On the contrary, despite using a much wider variety of precast components, the residential prefabrication projects' average WGR was nearly two times that of commercial projects. It might be the high proportion of precast wall and window components in commercial projects’ total construction volume that makes a difference in CWM.

4.2 The effects of different types of prefabrication on CWM

4.2.1 Spearman correlation analysis

Figure 3 visualizes the data, and the results of the tests conducted to compare WGRs as caused by different types of prefabricated components adopted. The dataset was the eight categories of prefabricated components defined in Table 3. The sample size was 114 projects. From the distributions of the components in the diagonal cells in Figure 3, it can be seen that seven categories had declining trends in the distribution, while the only exception was the façade category.

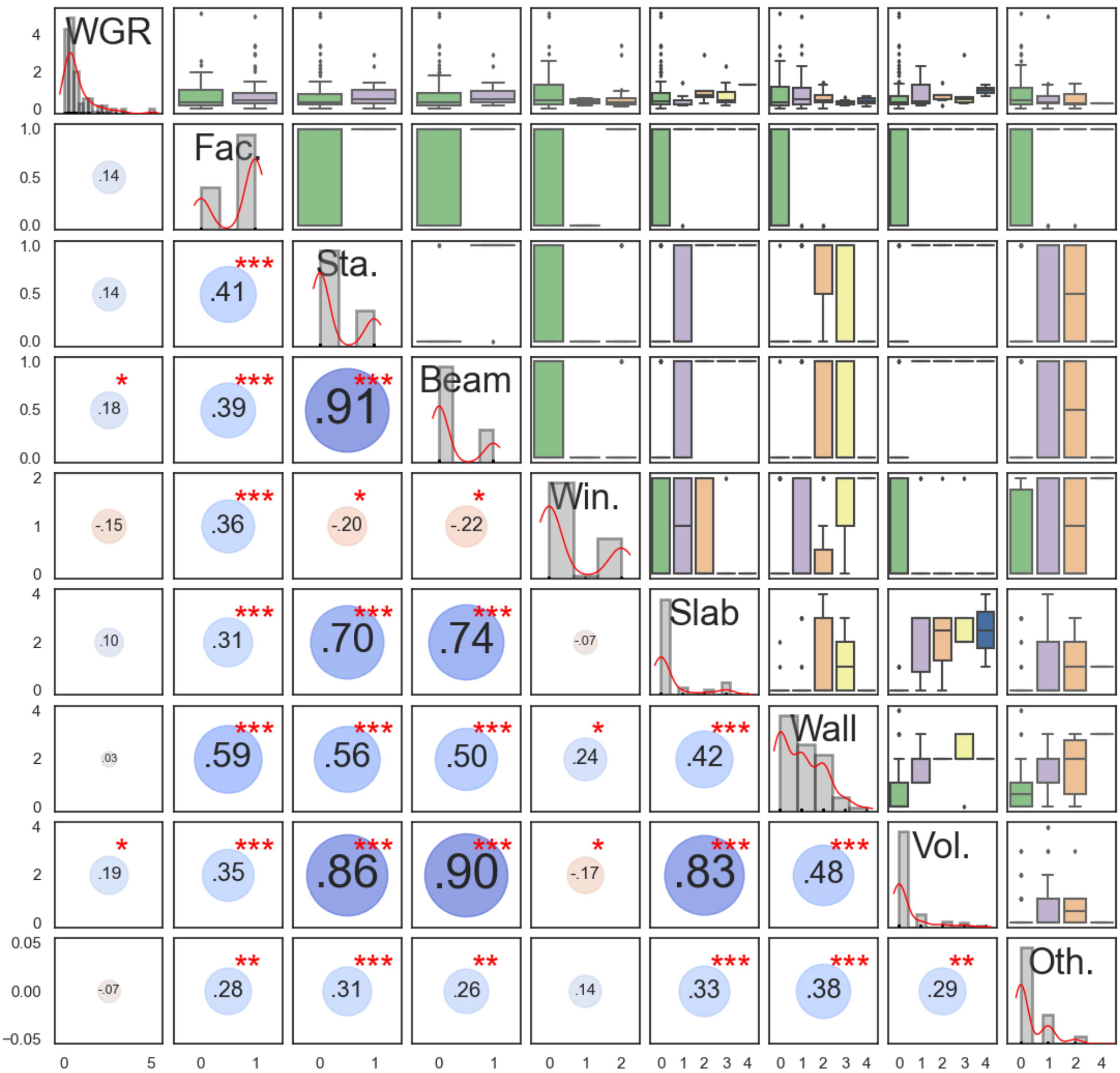

Figure 3. Results of Spearman correlation analyses, where each diagonal subfigure shows the distribution of a prefabrication category, the abbreviations are described in Table 3, a upper tringle subfigure at (i, j) presents the bivariate box-whisker plot between the i-th and j-th categories, and a lower tringle subfigure at (j, i) shows Spearman coefficient ρ and significance (*** $p \le 0.001$; ** $p \le 0.01$; * $p \le 0.1$, two-tailed, $N = 114$) between the i-th and j-th categories.

The first column of the cells in Figure 3 illustrates the major results of Spearman correlation analyses. Two significant positive correlations were found: (1) between the “volumetric” category and WGR, where the coefficient was $\rho = 0.19$ at a significance level $p \le 0.1$ ($N = 114$, two-tailed); and (2) between “beam” category and WGR, with coefficient being $\rho = 0.18$ at a significance level $p \le 0.1$ ($N = 114$, two-tailed). In other words, rather than contributing to waste reduction, the use of “precast beam” and “precast volumetric components” had the reverse effect by yielding a slightly higher WGR.

4.2.2 Independent samples t-tests

The lack of significant correlation between CWM and different types of prefabricated components may be attributed to their different levels of usage in different projects. For example, both Projects A and B have used two types of volumetric components. While the two volumetric components used by Project A comprise precast bathrooms and kitchens, the two volumetric components used by Project B were precast water tanks and refuse chutes. Given that each flat unit requires at least one bathroom and kitchen, an entire housing development can have up to hundreds or even thousands of precast bathrooms and kitchens. On the contrary, each building block only requires a few water tanks and refuse chutes. Therefore, it follows that the actual number of volumetric components used by Project A must be greater than that of Project B, so their effects on CWM should be different.

The ideal situation would be calculating the actual volumes of different types of prefabricated components vs. the volumes of cast in-situ construction to examine their different contributions to CWM. However, this is extremely onerous. One must read the drawings and calculate the proportions of prefabricated vs. cast in-situ volumes. Having considered the existence of such circumstances, in this study, we estimate the level of usage of “precast windows”, “slabs”, “walls”, and “volumetric components” based on their nature and intensity in a typical building. We then employ the independent samples *t*-test to compare the effects on CWM amongst projects with high, low, and no use of each of the four categories of prefabricated components. Table 5 lists out the results. Readers are reminded that the second column is estimated values while other columns contain factual data.

Table 5. Average WGRs among projects with varying levels of usage of precast window, slab, wall and volumetric components

Category of prefabricated component	Estimated level of usage	Average WGR (tons/m^2)	Stdev	Significance# of comparing the average WGRs of three levels	
Window	High	0.59	0.71	High vs Low usage:	0.70
	Low	0.43	0.19	Low vs No usage:	0.41
	No	0.91	1.00	High vs No usage:	**0.06**
Slab	High	0.90	0.74	High vs Low usage:	0.19
	Low	0.49	0.44	Low vs No usage:	0.40
	No	0.81	0.98	High vs No usage:	0.72
Wall	High	0.58	0.39	High vs Low usage:	**0.07**
	Low	0.92	1.06	Low vs No usage:	0.79
	No	0.86	1.05	High vs No usage:	**0.10**
Volumetric	High	0.96	0.79	High vs Low usage:	0.55
	Low	0.78	0.61	Low vs No usage:	0.96
	No	0.79	0.98	High vs No usage:	0.63

The *p* values of independent samples *t*-tests (Two-tailed)

Regarding precast window components, with a difference in average WGR of 0.32 ton/m^2, projects with greater estimated usage yield significantly lower average WGR than projects with no usage at all ($p \leq 0.1$). As for precast wall components, with differences in average WGR being 0.28 ton/m^2 and 0.35 ton/m^2 respectively, projects with greater estimated usage had significantly lower average WGR than projects with lower estimated usage and no usage at all ($p \leq 0.1$). It follows that incorporation of greater amounts of precast window and wall components is indeed conducive to waste reduction. Furthermore, with difference in average WGR being 0.01 ton/m^2 only, the average WGRs of projects with no and lower estimated usage of precast volumetric components were significantly equal ($p > 0.9$). This indicates that the deployment of only small amounts of precast volumetric components yields nearly no effect on waste minimization.

Precast window and wall components. There are no significant correlations between variety of precast window and wall components used and WGR. Nevertheless, the results of independent samples *t*-test illustrates that usage of greater estimated levels of precast window and wall components is conducive to construction waste minimization. This also provides a probable explanation for the higher popularity of precast bay windows, non-structural prefabricated external walls, and precast partition walls among the 114 sample projects. However, on closer inspection, all prefabrication projects with higher estimated levels of usage of precast window and wall components are residential developments. Therefore, it can only be inferred that usage of greater amounts of precast window and wall components can facilitate minimization of waste in residential building projects.

Volumetric precast components. Volumetric precast components, which have been widely promoted by the Government in recent years (HKEPD, 2009; HKSARG, 2018), were only used by public residential development projects. A probable explanation for the unpopularity of volumetric fabrication units among private developers is that most private development sites are situated in dense urban areas of Hong Kong, which lack temporary storage areas for such precast volumetric units. Public housing projects are often sizable to achieve the scale of the economy with land pre-assembled and provided freely by the Government. In this study, the results of Spearman correlation analysis suggest that projects incorporating wider variety of precast volumetric components tend to have slightly higher WGR. However, the independent samples *t*-test results suggest that the average WGR of projects using lower estimated levels of precast volumetric components were significantly equal to that of projects not using any precast volumetric components at all. This provides an additional explanation for the lack of popularity of precast volumetric components in private projects.

Precast beam component. Although precast beam is prevalent in public projects, the results of Spearman correlation analysis indicate that there is slight positive correlation between precast beam usage and WGR. This provides a probable explanation for the lack of popularity of precast beams in private projects.

5. Discussions

A cross-sectional comparison using a two-tailed *t*-test discovered that an overall 15.38% waste reduction was logged in prefabrication vs. conventional building projects. Further analyses also discovered that prefabrication led to a 17.58% waste reduction in private, a 15.05% waste reduction in residential, and a 52.15% waste reduction in commercial building projects. Although they are not statistically significant (i.e., $p < 0.05$), the analyses echoed with previous studies that prefabrication does have a positive effect on CWM. However, in any case, it seems that the reduction is not as "exciting" as reported before. A possible explanation is that in high-rise buildings the main structural parts are still using cast in-situ technology. The effect is not to be understood as the comparison between a purely cast in-situ building and a fully prefabricated building project. Nevertheless, the findings well echo Poon et al. (2004), which reported that prefabrication can replace around 20% wet trades in reducing the total amount of construction waste generation.

The research further investigated which category of precast components is more conducive to CWM. The Spearman correlation analyses discovered that projects using precast beams and volumetric components tended to generate slightly more waste. Additionally, we also deployed independent samples t-test to investigate the difference in average WGR between projects with varying estimated levels of usage of precast window, slab, wall and volumetric components. Contrary to the orthodox knowledge that modular precast components should be highly conducive to CWM, the average WGR of projects with greater usage of precast volumetric components were not significantly different from that of projects without such components. Furthermore, projects with greater usage of precast window and wall components have significantly lower average WGRs. It is coincident with the fact that they are also the most widely used ones in an overall building. The temptation is to say that it is not what type of prefabricated components but the proportion of prefabrication in the total construction volumes that matters to CWM.

Overall, the analytic results show that prefabrication has a positive effect on CWM. This effect is consistently observed in different groups of building projects (e.g., public vs. private; residential vs. commercial). Nevertheless, they are unbalanced samples with different numbers of building projects in each group. This research tells in greater detail and confidence which categories of prefabricated components have better effects on CWM if they are widely employed. This can provide insightful guidelines for informing policies to boost the adoption of this low waste construction technology. However, as an unfortunate fact, CWM is often of low prioritization in real-life construction (Wu et al., 2019b). Costs, buildability, and logistics and supply chain tend to be more important considerations than CWM in real-life practices.

6. Strengths and limitations of this study

The research has its strengths and weaknesses. Firstly, it is a strength that we are able to derive the objective measurement of waste generation in each project. Nevertheless, extrinsic factors affecting the total amount of waste generation, e.g., waste being recycled onsite, illegally disposed, and temporarily stored either onsite or offsite for future reuse, have not been considered. Secondly, this study is superior to previous studies in that it builds upon a sample of 114 real-life projects with an objective measurement of prefabrication adopted. However, we are only able to count the types of precast components and subcategories of different types of precast components being adopted. As the actual frequencies of usage and proportions in the total construction volumes are not obtainable for a more meticulous assessment, our categorization of projects with greater and lower usages of particular categories of prefabricated components was based on estimated rather than actual levels of usage. Thirdly, the mechanism through which prefabrication affects CWM is yet to be explored. It is desired to derive an index-style measurement of prefabrication to test the corollary mentioned above.

7. Conclusion

Prefabrication has long been acclaimed as a clean production technology to minimize construction waste generation. Previous studies have proved the positive effects of prefabrication on CWM. However, their data tends to be qualitatively collected using interviews, questionnaire surveys, or observations, which may not be ideal, given the fact that both prefabrication and construction waste generation can be objectively quantified. This paper aimed to revisit the effects of prefabrication on CWM by harnessing a set of valuable quantitative, secondary data collected from 114 building projects in Hong Kong.

Overall, it is discovered that prefabrication contributes to 15.38% reduction in construction waste. Further analyses found that prefabrication led to 17.58% waste reduction in private building projects, 15.05% in residential projects, and 52.15% in commercial building projects. Thus, this study reconfirms the positive effects of prefabrication on CWM as reported by previous studies. Unlike previous studies reporting an overall CWM rate though, this research was able to probe into the specific categories of precast components adopted as well as the contribution of varying levels of usage of four categories of prefabricated components to CWM. It is discovered that greater deployment of precast window (e.g., bay windows, window frames) and wall (e.g., non-structural prefabricated external walls, partition walls) components can significantly reduce the WGR. A possible explanation is their high level of adoption in the sample building projects. We thus draw a corollary the level of prefabrication usage is more important than what prefabricated components used in minimizing C&D waste generation. In comparison to existing studies, this study tells in greater confidence and clarity how prefabrication contributes to CWM. The research findings can be used as evidence to inform the policies (e.g., subsidiaries, saleable floor area exemption) to incentivize prefabrication adoption.

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