International Journal of Construction Management

ISSN: 1562-3599 (Print) 2331-2327 (Online) Journal homepage: https://www.tandfonline.com/loi/tjcm20

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International Journal of Construction Management, 2014
Vol. 14, No. 2, 113–121, http://dx.doi.org/10.1080/15623599.2014.899129

Prefabrication as a mean of minimizing construction waste on site

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Construction waste has become a major source of solid waste in Hong Kong. Thousands of tons of solid waste is produced every year from construction and demolition activities. Increasing generation of this waste has caused significant impacts on the environment and aroused public concerns. Therefore, minimization of construction waste has become a pressing issue. This paper aims to (i) reveal the status of construction waste, (ii) investigate the effectiveness of prefabrication in terms of waste reduction in replacing the traditional on-site production, (iii) examine the factors that help minimizing construction waste by the adopting prefabrication and (iv) explore the areas of waste reduction after adoption of prefabrication in comparison to traditional on-site production. The findings of a structured survey show that waste from 'poor workmanship' can be greatly reduced by adopting prefabrication in construction. Furthermore, after the adoption of prefabrication, waste generation can be greatly reduced in various on-site production activities, including plastering, timber formwork, concreting and reinforcement, with 100% waste reduction seen in plastering. Case studies are also used to demonstrate the effectiveness in the use of prefabrication to minimize construction waste in Hong Kong. It can be concluded that using prefabrication of building components is one of the most effective technologies of waste minimization.

Keywords: Prefabrication; construction; waste minimization; waste management; Hong Kong

Introduction

Waste generated from construction sites is one of the main components of landfills in Hong Kong, accounting for 38% of such space in 2004. The quantity of construction waste has been increasing steadily over the past few years to a record 20,490,000 tons in 2004 (Environmental Protection Department 2004). The adverse impact of the construction waste on the environment has now put the construction industry under considerable pressure to improve construction waste management (Vandecasteele & Van der Sloot 2011; Yuan & Shen 2011; Coelho & de Brito 2012). Because of the potential of environmental damage from landfill sites, decreasing landfill space and growing public opposition to reclamation work in Hong Kong, the current trend for disposal of solid waste is towards waste reduction measures, reuse and recycling (Tam et al. 2005; Hao et al., forthcoming; Jaillon & Poon 2008, 2009; Katz & Baum 2011; Kurisu & Bortoleto 2011; Lu & Yuan 2011). This is in line with the government's waste management strategies.

Prefabrication has been used in the construction industry for many years. The benefits of prefabrication are increasingly being recognized by the construction industry, particularly for its contribution to lean construction and cleaner built environment (Tatum 1986; Ting 1997; Tam et al. 2003, 2006, 2007b). The Hong Kong industry is adopting waste minimization strategies to achieve environmental and economic benefits and prefabrication as a general principle has been promoted by the Hong Kong government not only to improve buildability but also to reduce construction waste (Tam et al. 2004a, 2007a; Chiang et al., 2005; Jaillon et al. 2009). This indicates that prefabrication plays a vital role in contributing towards a clean built environment.

The Hong Kong Housing Authority adopted prefabrication in 1988 and its experience of using prefabrication has been positive in terms of time and environmental quality (Cheung et al. 1993; Ting 1997; Wong et al. 2003; Chiang et al. 2005). Because empirical studies have demonstrated a positive correlation between prefabrication and waste minimization (Cheung et al. 1993; Poon et al. 2001; Shen et al. 2002), it is clear that prefabrication is particularly beneficial for construction waste minimization.

Despite that fact that prefabrication can minimize waste generated on site from major construction trades, e.g., 100% waste reduction in plastering alone (Tam et al. 2004b), there still appears to be a reluctance in adopting prefabrication. This reluctance is mainly due to the initial high investment cost involved in manufacturing components (Chiang et al. 2005; Slavik & Pavel 2013; Yuan 2013; Yuan et al. 2013) and the fact that the non-modular design of most construction projects does not easily lend itself to the use of standardized prefabricated components (Shen et al. 2004). Although brief, the foregoing literature review clearly suggests that further adopting prefabrication has an important role to play to reduce

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construction waste on construction site (Tam et al. 2012; Yuan et al. 2012; Zhang et al. 2012; Guerrero et al. 2013; Yu et al. 2013). The review also provides compelling evidence to support the study of investigating how prefabrication can help realizing construction waste minimization.

Research aim and objectives

The aim of this paper is to explore the possibility to reduce construction waste by adopting prefabrication and the objectives are as follows:

- Investigating the effectiveness of prefabrication in terms of waste reduction in replacing traditional wet-trade practices.
- Examining the factors that help minimize construction waste by the adoption of prefabrication.
- Exploring the current waste reduction situations after adoption of prefabrication by comparing with in-situ construction.

Factors in minimizing construction waste by using prefabrication

The best way to deal with material waste is not to create it in the first place (Gavilan & Bernold 1994; Snook et al. 1995; Hong Kong Government – Environmental Protection Department 2006). Hence, to reduce construction waste, prefabrication has been considered as one of the most effective and efficient ways (Ting 1997). Shen and Tam (2002) and Tam et al. (2005, 2006) have studied several major causes of materials waste, including concrete, steel reinforcement, formwork and brick/block (see Table 1).

Table 1. Major causes of material waste

Application of construction material	Cause	Specification
Stone slabs	Cutting	Lack of tuning between sizes of different products,; imperfections of the product; waste-causing choices in design; lack of knowledge about building during the design stage (Tam et al. 2012)
	Shape	Imperfections of products; choices made in design about specifications of the product; method of transportation (Guerrero et al. 2013)
	Quality	Choice of a low-quality stone slab in design; lack of influence of contractors; lack of knowledge about building during the design stage (Ye et al. 2012)
	Order too much	Lack of possibilities to order small quantities (Tai et al. 2011)
	Storage and handling on construction site	Unpacked supply (California Integrated Waste Management Board 2011)
	Cracking during transportation	Unpacked supply (California Integrated Waste Management Board 2011)
Concrete	Ordering too much	Required quantity of products unknown due to improper planning (Tam & Tam 2007; Tam 2008)
	Loss during transportation	Required quantity of products unknown due to improper planning (Tam & Tam, 2007; Tam 2008)
	Scraping off	Method of laying the foundations of a building (Tam 2009)
Mortar	Scraping out	Negligent practice (Tam 2009; Iizasa et al. 2010)
	Mortar in the tub	Negligent practice (Tam 2009; Iizasa et al. 2010)
	Atmospheric influence	Negligent practice (Tam 2009; Iizasa et al. 2010)
	Specifications of the mortar	Short processing time (Environmental Council of Concrete Organizations 2006)
	Messing	Negligent practice; quantities of supply too high (Vyncke & Rousseau 1993)
Roof tiles	Sawing consequent from the design of the roof	Attention not paid to sizes of the products used in design; designers not familiar with possibilities of different products; types and sizes of the different products do not fit (Tonglet et al. 2004)
	Cracking during transportation	Negligent handling by the supplier (Shima et al. 2004)
Reinforcement	Cutting	Use of steel bars of sizes that do not fit (Tam & Tam 2008)
Formwork	Cutting	Use of timber boards of sizes that do not fit (Tam & Tam 2008)
Brick/block	Cutting	Use of sizes that do not fit (Alonso-Santurde et al. 2012)
	Damaged during transportation	Unpacked supply (Alonso-Santurde et al. 2012)

Cheung et al. (1993) also identified the following six major causes of material waste on on-site production activities: (i) cutting, (ii) over ordering, (iii) damage during transportation, (iv) lost during installation, (v) poor workmanship and (vi) change of design.

To assess the significant levels of the causes of material waste, an interview survey was conducted with thirty-one senior construction practitioners, who were asked to comment on the levels of waste reduction in various reasons for the reduction in comparing prefabrication with other on-site production activities including concreting, bricklaying, plastering/screeding, tiling and steel bar fixing. The practitioners included senior project managers, project managers, architects, senior quantity surveyors and engineers, with about 15–25 years of on-site experience. Respondents were asked to give their response on the significant level on a scale of 1 to 5, with 1 indicating least significant and 5 indicating extremely significant. The results are given in Table 2.

As per the data presented in Table 2, 'poor workmanship' is considered as the most important cause leading to the waste of plastering/screeding and tiling, with a weighted average score of about 3.40 and 3.21, respectively. In concreting and bricklaying, poor workmanship is considered as the second important cause with weighted average scores of about 3.55 and 2.95, respectively. While explaining the importance of workmanship on these trades, e.g., plastering requires applying various layers and thus improving the performance of the outlook, one of the interviewed engineers said that the techniques of the workers directly affect the final quality of plastering work. As the quality of these trades is based on the performance of the workers, improving the quality of workers by training, certification and skill development is essential in cutting construction waste. 'Damage during transportation' in bricklaying is the major cause of waste, which can be reduced or eliminated by replacing site bricklaying with dry wall panel systems.

In tiling, waste due to 'cutting', 'over-order' and 'poor workmanship' can be reduced after using prefabricated building components. However, with simple applications of modular dimensioning on tiling, a potential reduction in waste can also be achieved. The reduction of waste in rebar is considered moderate. However, rebar is of less concern in waste minimization as it is recyclable.

In general, construction waste resulting from the major causes, namely, cutting, over order, damage during transportation, loss during installation, poor workmanship and change of design, can be effectively reduced by adopting prefabrication.

Comparing waste levels between on-site production and prefabrication

Prefabrication technology has been mainly adopted by public housing developments in Hong Kong, which have the resources and expertise to risk introducing new technology, but has not been widely accepted by the private sector (Tam et al. 2005, 2006). To examine the advantages of prefabrication for private developments, four private building projects (one hotel, one residential tower and two commercial buildings), which applied, to a certain extent, some prefabrication techniques, were selected for this study. Details of these four projects are given in Table 3.

The levels of prefabrication applied in the four projects were identified after interviewing the project managers of these projects. Table 3 shows the various prefabrication elements for these projects. The most common prefabricated elements are facade and staircase units. During the construction of the precast facades, aluminium window units were cast monolithically so that any water leakage through joints can be minimized. "Lost" form (permanent form) for the entire external load-bearing wall and precast balcony were adopted for Project 2. Plastering, tiling and scaffolding work were minimized, thus enhancing site productivity. Precast balconies were pre-finished with tiling in the prefabrication yard by adopting a semi-precast technique in which the final structural portion of the unit was cast in-situ with the supporting beams. Projects 2, 3 and 4 adopted a dry wall system for internal partitions onto which a thin layer of skin coating (1–2 mm thick) was applied before the final painting, thus reducing site construction waste arising from the traditional on-site production activities.

Off-site building services fabrication was used as the prefabrication technique for Project 4. About 95% of building services were fabricated off-site, including integrated lighting and air-conditioning outlets, low-glare fluorescent lights with electronic ballasts, direct digital control variable air volume system, heat absorbing and solar reflective double-glazed curtain walls, semi-precast sprinkler heads, fully recessed lighting unit and suspended acoustic ceiling panel. The project manager of this project suggested that this results in significant cost savings.

To examine waste levels, these four projects were compared with similar projects (identified with the help of the four project managers) that followed the traditional on-site production approach. Data were collected through a series of structured interviews with the project managers, our site observations and recording. Four major site operations including plastering, timber formwork, concrete and reinforcement were investigated in this study, excluding the off-site trades at the prefabrication yards and other auxiliary services such as additional transport and hoisting facilities.

Table 2. Response on reasons leading to waste for various on-site production activities

Trade	Causes	Interviewees' response: Least significant '1'	Fairly significant '2'	Significant '3'	Very significant '4'	Extremely significant '5'	Mean
Concreting	Over order	10%	10%	15%	35%	30%	3.65
	Damage during transportation	20%	35%	10%	10%	25%	2.85
	Lost during installation	20%	25%	20%	10%	25%	2.95
	Poor workmanship	15%	15%	15%	10%	45%	3.55
	Change of design	40%	20%	15%	13%	12%	2.37
Bricklaying	Cutting	30%	25%	15%	10%	20%	2.65
	Over order	40%	25%	15%	15%	10%	2.45
	Damage during transportation	15%	15%	15%	10%	45%	3.55
	Lost during installation	20%	25%	20%	10%	25%	2.95
	Poor workmanship	20%	25%	20%	10%	25%	2.95
	Change of design	10%	35%	30%	15%	10%	2.8
Plastering/ screeding	Lost during installation	22%	15%	23%	20%	20%	3.01
	Poor workmanship	10%	20%	15%	30%	25%	3.4
	Change of design	30%	15%	30%	20%	5%	2.55
Tiling	Cutting	15%	15%	30%	30%	10%	3.05
	Over order	10%	15%	37%	25%	13%	3.16
	Poor workmanship	6%	25%	25%	30%	14%	3.21
	Change of design	25%	25%	35%	10%	5%	2.45
Rebar fixing	Cutting	19%	4%	50%	25%	2%	2.87
	Over order	30%	25%	25%	10%	10%	2.45
	Poor workmanship	55%	10%	15%	10%	10%	2.10
	Change of design	32%	30%	23%	10%	5%	2.26

Table 3. Details of projects with high level of prefabrication

Project title	Project 1: hotel redevelopment	Project 2: residential building	Project 3: Commercial building A	Project 4: Commercial building B
Gross floor area	9514 m^2	56,756 m^2	181,310 m^2	31,140 m^2
Scope of the project	A 31-storey hotel comprising three-level podium and a 28-storey guestroom tower	Two blocks of residential buildings of 48-storey high and one-level podium.	An 88-storey office and a 5-storey car parking	A 36-storey grade A office building, including a 2-storey podium and a storey of mechanical and electrical (M/E) floor
Construction methods	A conventional method is adopted for the guestroom tower, while prefabrication method is used for the podium	A conventional method is adopted for the podium, while prefabrication is applied to the residential towers	A conventional method is adopted for the car parking, while prefabrication method is applied for the 88-storey office tower	Semi-precast elements at typical floor, in which it splits into two portions, one by in-situ construction and the other by prefabrication
Prefabricated building components	Prefabricated slab	Precast facade	Structural steel frame	Precast staircases
	Staircase	Lost form	Unitized curtain wall system	Precast plank
	Precast facade	Precast balcony	System formwork for core wall and mega column	Semi-precast beam
	System formwork	Staircase	Super deck material platform	Jump lifts
		Dry wall system	Precast staircase	Off-site prefabricated building services components
			Dry wall system	Dry-wall system
Cycling time	7-day cycle	4-day cycle	7-day cycle	4-day cycle
Location of prefabrication yard	Yuen Long	Dong Guan	Mainland China	Mainland China

Waste levels of building materials can be defined as the remains of the on-site materials. Equations (1) and (2) can be used to calculate the percentage of waste levels for projects that adopt prefabrication method and for projects that adopt the traditional on-site production approaches, respectively:

$$W_p = \frac{M_{Dp} - M_{Up}}{M_{Dp}}(100\%) \tag{1}$$

$$W_e = \frac{M_{De} - M_{Uc}}{M_{Dc}}(100\%) \tag{2},$$

where

- W_p and W_c denote the percentage of material waste for projects of prefabrication and projects of the traditional on-site production, respectively,
- M_{Dp} and M_{Dc} are the amounts of material delivered on site for projects of prefabrication and project of the traditional on-site production, respectively, and
- M_{Up} and M_{Uc} are the amounts of material used for built works for projects of prefabrication and project of the traditional on-site production, respectively.

Improvements in waste levels are measured by a relative index, denoted as W:

$$W = \frac{W_c - W_p}{W_c}(100\%) \tag{3}$$

The relative indices of the various trades for these projects are summarized in Table 4.

Waste resulting from hacking off concrete from grout leakage and dislocation of formwork, from excessive plastering to hide surface unevenness and from excessive site mixed mortar could be completely avoided for Projects 1, 3 and 4. For the hotel project that adopted prefabrication method, only 1–2 mm skim coat, instead of the usual 15–20 mm, of plastering

Table 4. Relative indices on improvement in waste for various trades

	Traditional on-site production			Prefabrication			
	M_{Dc}	M_{Uc}	W_c	M_{Dp}	M_{Up}	W_p	W
Project 1: Hotel redevelopment							
Plastering (m^2)	7,200	6,800	5.56%	600	600	0.00%	100.00%
Timber formwork (m^2)	16,500	14,000	15.15%	2,350	2,300	2.13%	85.96%
Concrete (m^3)	7,700	7,000	9.09%	1,360	1,300	4.41%	51.47%
Reinforcement (ton)	1,370	930	32.12%	350	300	14.29%	55.52%
Project 2: Residential building							
Plastering (m^2)	250,000	180,000	28.00%	600	580	3.33%	88.10%
Timber formwork (m^2)	400,000	285,000	28.75%	2,000	1,850	7.50%	73.91%
Concrete (m^3)	50,000	45,000	10.00%	500	480	4.00%	60.00%
Reinforcement (ton)	6,500	6,000	7.69%	400	380	5.00%	35.00%
Project 3: Commercial building A							
Plastering (m^2)	5,000	3,000	40.00%	400	380	5.00%	87.50%
Timber formwork (m^2)	6,000	4,000	33.33%	1,500	1,400	6.67%	80.00%
Concrete (m^3)	2,200	2,000	9.09%	500	480	4.00%	56.00%
Reinforcement (ton)	1,250	1,000	20.00%	200	180	10.00%	50.00%
Project 4: Commercial building B							
Plastering (m^2)	9,500	8,000	15.79%	700	700	0.00%	100.00%
Timber formwork (m^2)	16,000	10,000	37.50%	2,000	1,900	5.00%	86.67%
Concrete (m^3)	13,500	12,000	11.11%	1,000	950	5.00%	55.00%
Reinforcement (ton)	4,500	4,200	6.67%	500	480	4.00%	40.00%

was applied, yielding 100% waste reduction in this process. Furthermore, timber formwork was reduced by about 73.91%–86.67%, causing significant reduction in timber scraps. Compared with the traditional on-site production construction methods, steel formwork was used in prefabrication yards – the increase in times of reuse results in significant reduction in material waste. Waste resulting from concrete was also significantly reduced by about 51.47%–60% as the prefabricated products were cast off-site. Although waste of steel bars can be reduced from about 35% to 55.52%, the saving was not significant as steel bars from construction sites can be recycled.

While examining the material waste levels between the traditional on-site production and prefabrication construction in Hong Kong, it was found that the various on-site production activities can effectively reduce the waste by adopting prefabrication method. Furthermore, standardized designs should also be adopted to facilitate the use of prefabrication, thus reducing the material waste.

Although we found that by adopting prefabrication there was significant reduction in waste levels, there were also several hindrances in the development of prefabrication as described by the interviewees.

The congested roadwork in Hong Kong affects timely delivery of prefabricated components, which impinge on the progress of the tight construction schedule. Lack of experience of the labour and the frontline supervisory staff in handling prefabrication takes a longer learning curve/time before arriving at planned cycling times. Designers and consultants are very cautious and thus very demanding in managing prefabrication works. Proper training and education in this area are strongly required. High land costs also form one of the major difficulties in locating prefabrication yards in Hong Kong.

Prefabrication will only be successful when contractors and developers can enjoy cost savings. Interviewees suggested that cost was the key factor at this critical moment of economical downturn. Prefabrication will bring effective cost saving only when the following processes or methods are implemented:

(1) Fully mechanized construction process using heavy plants.
(2) Turning construction into an assembly line industry rather than on-site production.
(3) Use of recycle materials for the prefabricated components.

In addition, the following three main stimulators are required to encourage the use of prefabrication (Ting 1997; Poon 2000; Ho 2001):

(1) *Environmental issues*: When more stringent environmental control and regulations are forthcoming, prefabrication is one of the ways to facilitate long-term waste minimization and reduction.
(2) *Construction costs*: Introducing more productive and lean construction methods can reduce the construction cost effectively and reduce the burden incurred due to high initial investment (Shen & Tam 2002).
(3) *Government incentives*: Granting relaxation to the gross floor areas for projects employing prefabrication elements, e.g., discounting the area occupied by facade units (Hong Kong Government – Environmental Protection Department 2006), will encourage the use of prefabrication. Moreover, tighter control on workmanship, allowable tolerances, homogeneity and allowable rework will favour the adoption of prefabrication.

Conclusion

This paper shows that adopting prefabrication can effectively reduce construction waste, and also demonstrates that the causes of waste generation, i.e., cutting, over order, damage during transportation, lost during installation, poor workmanship and change of design, can be greatly reduced after adopting prefabrication. Poor workmanship was found to process greatest saving as it is the major cause of waste generation for on-site production activities, especially in plastering/screeding and tiling work. Four private building projects with high levels of prefabrication were used as case studies to illustrate the effectiveness of prefabrication in waste minimization. It has been found that up to 100% of waste can be reduced in plastering. Timber formwork could reduce waste from about 73.91% to 86.87%. Waste resulting from concrete can be reduced from about 51.47% to 60%. Waste of steel bars can be reduced from about 35% to 55.52%. It should be noted that waste can be significantly reduced by using prefabrication method rather than the traditional on-site production activities. However, various hindrances are encountered in the adoption of prefabrication, including the long haulage of prefabricated components, the lack of experiences of the industry and high land costs in locating prefabrication yards. Suggestions have been made to help push the use of prefabrication, including implementing more stringent environmental control and regulations, highlighting the savings that result from more productive lean construction methods, and granting relaxation to the gross floor area for projects are required to change the attitude of the construction industry. After all, the prospects of using more prefabrication techniques are very promising because prefabrication will ultimately help to lower high construction costs through mechanization, standardization and industrialization.

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