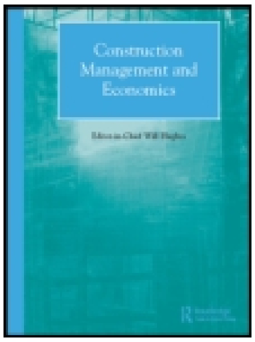

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Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study

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The construction industry in Hong Kong heavily relies on conventional cast in-situ construction involving extensive use of timber formworks and wet trades. In 2001, the Construction Industry Review Committee (CIRC) report described the construction activities in Hong Kong as 'labour intensive, dangerous and polluting', in which 'built products are rarely defect-free'. Globally, however, the recent trend is prefabrication, which is being increasingly used in the building industry, alleviating some of the environmental burdens associated with conventional construction. The sustainable construction aspects of adopting prefabrication in high-rise buildings are examined, and the economic, environmental and social aspects of using prefabrication are assessed. A questionnaire survey was administered to experienced professionals and case studies of seven recent residential and non-residential buildings in Hong Kong were conducted. The findings revealed that environmental, economic and social benefits of using prefabrication were significant when compared to conventional construction methods. This implies that a wider use of prefabrication techniques could contribute to sustainable construction in a dense urban environment like Hong Kong.

Keywords: High-rise buildings, Hong Kong, precast concrete, prefabrication, sustainable construction.

Introduction

Sustainable construction

Kibert (1994) defined sustainable construction as 'the creation and responsible management of a healthy built environment based on resource efficient and ecological principles'. In recent years, sustainable development and sustainable construction have become a growing concern throughout the world. Construction has significant and irreversible effects on the environment such as (1) the use of land and virgin land (e.g. forests, wetlands) which often entails losses of biodiversity and soils; (2) the extensive use of natural resources, many of which are non-renewable ones; (3) the pollution of air and water reserves; (4) the consumption of water and energy; (5) waste generation; and (6) the generation of noise by construction activities (Ofori *et al.*, 2000).

Hong Kong is a compact city and one of the most densely populated places in the world. As available land is limited and land price is expensive, the construction of high-rise buildings is prevalent in Hong Kong. The built environment (urban environment) in Hong Kong is one of the most densely populated places despite the fact that only 20% of the whole territory is developed. The area of Hong Kong is 1104 square kilometres and the average population density was about 6420 persons per square kilometre in 2005. But in some urban districts it went up to over 50 000 people per square kilometre. With such urban compactness, sustainability and sustainable construction is indeed an increasing concern in Hong Kong.

Hong Kong construction industry

The construction industry is a major industry in the Hong Kong economy, totalling about 2.9% of the GDP (in 2005), and employing about 8% of the workforce (Census and Statistics Department, 2007). In 2001, the Hong Kong construction activities were described in the Construction Industry Review Committee report as 'labour intensive, dangerous and polluting' (CIRC, 2001). Most of the buildings in Hong Kong are still built with labour-intensive in-situ construction methods, in which the quality control is less efficient than in a

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factory environment. The construction industry is also considered a dangerous industry, and has the highest level of accident injuries and fatalities. The accident rate per 1000 workers was about 59.9 in 2005 (Labour Department, 2006). Comparatively, the accident rate per 1000 workers in Hong Kong is twice that of the UK and about 10 times worse than in Japan (Rowlinson, 2004).

Indeed the construction activities essentially disturb the environment, generating nuisance such as dust, noise, muddy site run-off, and considerable amount of waste. In particular, conventional construction methods involve the use of significant amounts of timber formworks and wet trades producing large quantities of waste on-site.

In Hong Kong, the management and disposal of construction waste is a major environmental issue as the availability of suitable disposal area is scarce. In 2005, about 21.5 millions tonnes of construction waste were generated, of which 11% was disposed of to landfill and 89% to public filling areas (reclamation projects). The composition of construction waste varies according to the type and scale of the building works. In recent years, construction waste in Hong Kong generally consisted of 70% of soft inert materials (soil, earth and slurry) which can be reused as fill materials in reclamation and earth filling works, 12%–15% of hard inert materials (rocks and broken concrete) which can be reused or recycled, and 15%–18% of non-inert waste (metal, timber and packaging waste) which can be recycled if not contaminated (Legislative Council, 2006). However, currently most of the non-inert waste is disposed to landfill and not recycled. Over the last decade, the generation of construction waste has more than doubled. With the current rate, the capacity of landfills and public filling areas will be exhausted by 2011–15 and by 2008 respectively (EPD, 2006). The government has recently implemented construction waste reduction measures, such as the requirement for public work contractors to set up waste management plans and comply with the trip ticket system. The trip ticket system is a recording system for trucks transporting waste, ensuring that each type of waste is directed to the appropriate facility for reuse, recycling, recovery or disposal. The recycling of hard and inert construction waste as recycled aggregates and rock fills are also being promoted. In late 2005, the government initiated a charging scheme for construction waste disposal. The charges are HK$125/tonne (or US$16/tonne) of waste disposed to landfill, HK$100/tonne (or US$13/tonne) to sorting facilities, and HK$27/tonne (or US$3.5/tonne) to public fill reception facilities. The public fill reception facilities include facilities such as public filling areas (designated areas that accept public fill for reclamation purpose) and fill banks (areas allocated for temporary stockpile of public fill for later use).

In addition, the government also encourages the use of green building technologies and prefabrication. In 2001, the CIRC report recommended a wider use of prefabrication in buildings to alleviate some of the problems associated with in-situ construction, such as dirt, noise and construction waste generation, and lower quality control on-site. In 2001 and 2002, the Hong Kong government also introduced incentives schemes to promote the use of green and innovative building technologies and prefabrication (Buildings Department, 2001, 2002). These incentive schemes established a list of green features, including non-structural prefabricated external walls that might be exempted from gross floor area (GFA) and site coverage (SC) calculations under the Building Ordinance.

Prefabricated building systems

Prefabrication is a manufacturing process, generally taking place at a specialized facility, in which various materials are joined to form a component part of the final installation (CIRIA, 1999). Precast construction was made feasible with the advancement of adapted equipment for transportation and erection. Worldwide, in 1996, the highest level of use of precasting was located in Denmark since the introduction of modular coordination legislation in the 1960s (MOM and MND, 1999). In Asia, Japan and Singapore achieved a precast level of 15% and 8% respectively in 1996, but Singapore aims to achieve a figure of 20% by 2010 to increase productivity and buildability (CIDB, 1992; BCA, 2005).

Recent overseas studies have acknowledged the benefits of prefabrication in buildings (Yee, 2001a, 2001b; BRE, 2001; Gibb and Isack, 2003; Pasquire *et al.*, 2005; Blismas *et al.*, 2006; Goodier and Gibb, 2007). Benefits of prefabrication in the literature tend to focus on cost, productivity and quality. Only a limited number of studies assess the combination of economic, environmental and social benefits of using prefabrication in buildings, especially in the case of high-rise buildings in high-density urban environments. Moreover, these studies have provided limited quantitative data. Although recent tools help in assessing the benefits of prefabrication and off-site production (Blismas *et al.*, 2003), there seems to be a lack of understanding of the full benefits of prefabrication within the construction industry (Goodier and Gibb, 2007).

In Hong Kong, prefabricated buildings were first developed along with the public housing programme. In the mid-1980s, prefabrication combined with standard modular design, was introduced in public housing projects (Mak, 1998). Since then, the Hong Kong Housing Authority (HKHA) has encouraged the adoption of precast elements, reusable formwork and other environmentally friendly building technologies in all public housing contracts. Major precast elements used are precast facades, staircases, parapets, partition walls, semi-precast slabs and, more recently, volumetric precast bathrooms. In 2002, precast components accounted for about 17% of the concrete volume used in public housing projects (Chiang *et al.*, 2006). In 2005, a pilot project extended the use of precasting to 65% including the use of precast kitchen and structural walls (HKHA, 2005). The majority of previous studies focused on examining innovations and performances in public housing blocks built with standard designs (Chan and Lee, 1998; Mak, 1998; Wong and Yau, 1999; Lam, 2002; Chan and Chan, 2002, 2003; Chiang *et al.*, 2006).

In contrast, the private sector in Hong Kong still predominantly adopts conventional construction methods involving the use of timber formwork, considerable amount of wet trades and bamboo scaffolding. Although the use of prefabrication techniques has increased in the private sector since the establishment of incentive schemes in 2001 and 2002 (Buildings Department 2001, 2002), only a limited number of studies have examined and quantified the benefits of adopting prefabrication techniques in private developments (Fong *et al.*, 2003). In fact, Chu and Sparrow (2001) did examine the advantages and limitations of using prefabrication in private residential buildings. However, this study was confined to qualitative data without case studies. Tam *et al.* (2007) have quantified, by using a case study, the reduction of wastage level on site by adopting prefabrication in buildings. However, the data gathered were somewhat limited.

This article, therefore, seeks to bridge some of the knowledge gaps in the quantification of the benefits of prefabrication in dense high-rise urban environments involving non-standard designs. The objectives of the paper are to: (1) examine the present industry practices and the views from building professionals regarding the use of prefabrication in buildings in Hong Kong; (2) study sustainable construction aspects of using prefabrication techniques in high-rise buildings located in dense urban environments; (3) assess the environmental, economic and social benefits and limitations of using prefabrication, and compare prefabrication with conventional construction methods.

Research method

The data collection process consisted of an industry questionnaire survey, and detailed case studies of recently completed residential and non-residential buildings in Hong Kong. The industry questionnaire survey aimed to investigate the perspective of the construction industry in general regarding the use of prefabrication in buildings and the perceived advantages and limitations in dense urban environments such as Hong Kong. The case studies attempted to gather information regarding the present practices of the industry and included on-site observations, project data collection, face-to-face interviews and specific project-oriented questionnaire surveys. Similar issues were considered in the industry questionnaire survey and the case studies. The results gathered were presented using a spider chart representation (Figures 1 and 2) which permitted the validation of the collected data.

Industry questionnaire survey

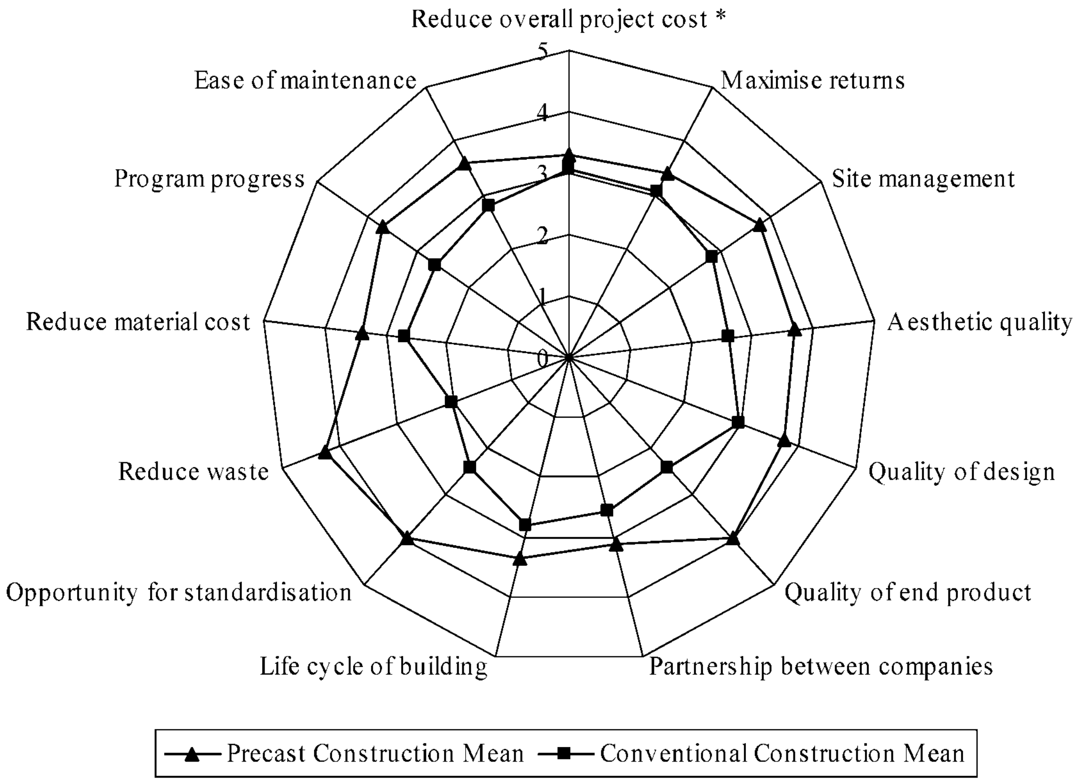
For the industry survey, a questionnaire was developed from key issues identified in the literature and gathered from interviews with professionals. A pilot survey was conducted with experienced contractors, architects, engineers and prefabrication manufacturers in order to confirm the final questionnaire version. The questionnaire was then administered by email to 354 building professionals working in registered private companies and government departments. The survey was conducted over a period of five months in 2005. As presented in Table 1, there were 84 respondents thus resulting in a response rate of 24%. The majority of respondents were experienced engineers (28%), architects (21%) and builders (18%) from private and government sectors. In the questionnaire, the respondents were requested to assign an appropriate rating on a scale of 1 to 5, from the highest to the lowest level, against each factor to reflect the importance of the factors in each question. For each factor, the mean was calculated based on weightings from (+1) being 'least important' to (+5) being 'most important'. The questionnaire was specifically devised to allow a comparison between prefabrication and conventional construction method. A sampling distribution of the difference of means for conventional and prefabrication construction was calculated to test the significance of differences between results obtained for both construction methods (Equations 1 and 2). Calculated t-value:

$$t_{Cal} = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{S_{x1}^2}{n_1}} + \sqrt{\frac{S_{x2}^2}{n_2}}} \quad (1)$$

where $\overline{x_1}$ = mean for conventional construction;
$\overline{x_2}$ = mean for prefabrication;
S_{x1} = standard deviation for conventional construction;
S_{x2} = standard deviation for prefabrication;
n_1 = sample for conventional construction;
n_2 = sample for prefabrication.

The critical value:

$$t_{Critical} = t_{n_1+n_2-2,\alpha/2} \quad (2)$$



* No significant evidence to support that the means in Precast and Conventional construction are different (see Table 6). Rating scale: 5 'most important' to 0 'least important'.

Figure 1 Most important considerations when using precast and conventional construction in industry survey 2005

From the statistical table, the critical values of t-tests are 1.96 and −1.96 with 95% of confidence interval. If the calculated t-value falls within the critical values, there is no significant evidence to support that the means are different.

Face-to-face interviews were conducted with professionals in the building industry to further validate the data collected through the survey.

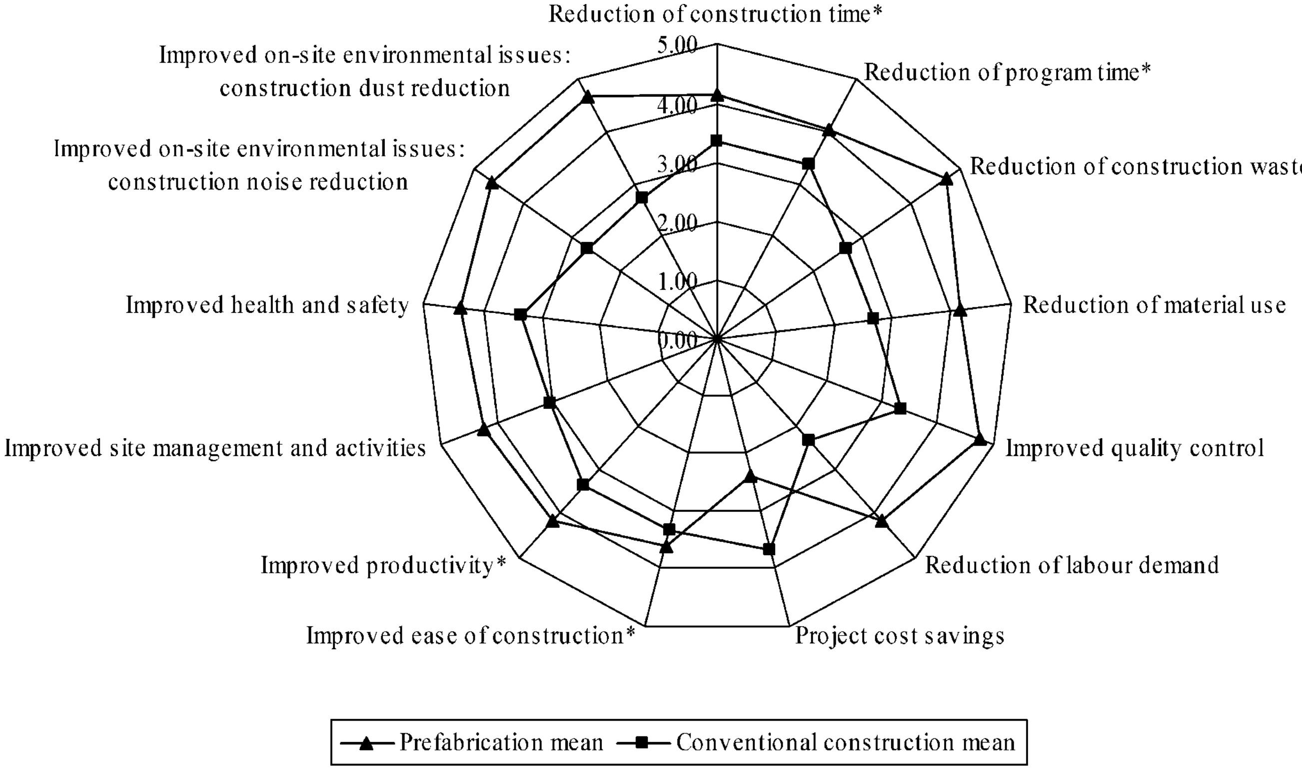
Detailed case studies

The case study method comprised an investigation of seven recent high-rise building projects using conventional or precast construction methods. Five residential and non-residential projects using prefabrication in Hong Kong were investigated. Two developments using conventional construction were also selected to ascertain valid comparison with the prefabricated buildings. The selection criteria for the case studies included building types and height, year of completion and project size. The seven projects are described in Tables 2 and 3.

The data collection process for each project consisted of data gathered from the literature as the first step, then a project-oriented questionnaire survey and finally face-to-face interviews with the project clients, architects, contractors, engineers as well as precast element manufacturers (Table 4). In addition, site observations were conducted at six construction sites and one precast manufacturing plant. Drawings and project documentation were collected from the architects, clients, contractors and the Buildings Department.

The project-oriented questionnaire was administered by email or in person, and consisted of six questions on the following topics: (1) reasons for adopting prefabrication in the project; (2) benefits; and (3) limitations of using prefabrication. The questions were similar to those used in the industry survey described above in order to allow valid comparison. Similar to the industry survey, the respondents in the project-oriented questionnaire survey were requested to assign an appropriate rating on a scale of 1 to 5, from the highest to the lowest level, against each factor. Equations 1 and 2 were used to compare the results obtained from projects adopting prefabrication as opposed to those adhering to conventional construction methods. The critical values of t-tests, however, varied (Tables 5 and 6). The comparison between prefabrication and conventional construction were also discussed during face-to-face interviews.

An estimation of material conservation for timber formworks when prefabrication techniques were



(Rating scale: 5 'most important' to 0 'least important').

* No significant evidence to support that the means in precast and conventional construction are different (see Table 6).

Figure 2 Advantages when using precasting or conventional construction in selected projects

adopted in the selected projects was conducted. The quantity and volume of timber formwork saved by using prefabrication was measured for each project. The dimensions of precast elements were available from the buildings' structural plans, and the required timber volume to build these elements was calculated by following the British Standards, the General Specifications used in Hong Kong, and the *Code of Practice for Structural Use of Concrete* (Buildings Department, 2004). According to the General Specifications, the timber formworks can be reused for a maximum of nine times. The timber formwork system used for the calculation was standard sanded Douglas fir exterior plywood, 7-ply 19mm thick (BS 5975:1996) (BSI, 1996, p. 83). The dimensioning and spacing of the primary and secondary members to stiffen the plywood were calculated from the BS 5975:1996) (BSI, 1996, pp. 88–91), for slabs, beams, columns and facades/walls. The cutting wastage was also taken into account for each type of element. The cutting wastage for slabs and beams was estimated at 5% for plywood and 7% for softwood sawn-timber stiffener. The cutting wastage for walls and columns was estimated at 5% for plywood, and 10% for softwood sawn-timber stiffener (Poon and Yip, 2005). Potential material and cost savings by using prefabrication in lieu of timber formwork were also discussed and estimated for each case study (Table 7).

Other aspects of the building performance for the selected prefabricated buildings were investigated. These comprised the construction cost and time, the labour requirement on-site and the accident rate per 1000 workers. For each project, the data were gathered through face-to-face interviews with the project manager, the architect and/or the contractor (Table 8). Sustainable construction aspects of prefabrication are discussed below with regard to economic, environmental and social aspects.

Table 1 Distribution of questionnaire responses and response rates for the industry survey

Respondent	Responses	Percentage	Response rate
Contractor	15	18%	18%
Architect	18	21%	10%
Engineer	23	28%	43%
Building surveyor	5	6%	25%
Quantity surveyor	10	12%	48%
Others	13	15%	
Total	84	100%	24%

Table 2 Details of residential building projects using conventional construction and prefabrication

	Conventional construction	Precast construction	
	Project 1	Project 2	Project 3
Project description	Eight 35-storey towers providing 1404 units	Two 48-storey towers & 2-level podium, providing 442 units	One 32-storey tower & 2-level podium, providing 310 units
Year of construction	2002–2004	2001–2003	2002–2005
Site area (m^2)	–	5714	6320
CFA (m^2)	119 900	56 000	18 960
Podium construction	–	Conventional construction	Conventional construction
Tower construction	Conventional construction	Prefabrication & aluminium/steel system formworks	Prefabrication & steel system formwork
Precast % (by volume)	0%	60%	50%
Type of prefabricated elements	–	-Precast staircase & façade -Lost form panels -Semi-precast balcony -Dry wall system	-Semi-precast slab & balcony -Precast staircase & staircell -Precast facade & bay window -Precast structural wall -Precast bathroom & kitchen
Construction cycle	5 days/floor	4 days/floor	5 days/floor
Construction duration	28 months	20 months	–
GFA exempted under JPNs/CFA	–	10%	6%

Results and discussion

Benefits of using prefabrication techniques in dense urban environments

In the industry and the project-oriented surveys, the results consistently revealed that improved quality control and construction waste reduction were the two most important benefits when adopting prefabrication in buildings. As seen by the actors, other major benefits mentioned included improved health and safety, better onsite environmental conditions (less dust and lower noise), as well as a reduction in labour demand, construction time

Table 3 Details of non-residential building projects using conventional construction and prefabrication

	Conventional construction	Precast construction		
	Project 4 Institutional	Project 5 Institutional	Project 6 Office (Grade A)	Project 7 Hotel
Project description	One 14-storey tower 3-level podium	One 17-storey tower 3-level podium	One 36-storey tower 2-level podium	One 33-storey tower 3-level podium 274 units
Year of construction	2003–2005	2005–2007	2001–2003	–2001
Site area (m^2)	3500	4386	1488	617
CFA(m^2)	30 821	30 404	31 140	9514
Podium construction	Conventional construction	Conventional construction	Conventional construction	Conventional construction
Tower construction	Conventional construction	Precasting for structural & non-structural elements	Precasting & steel/aluminium formworks	Precasting & steel large panel formwork
Precast % (by volume)	–	47%	70% (floor area)	
Type of prefabricated elements	GRC panels	-Semi-precast slab -Precast beams & column -Precast staircase -Precast facade	-Semi-precast slab -Precast beams -Precast staircase	-Semi-precast slab -Precast staircase -Precast facade -Dry wall panels
Construction cycle	6 days/floor	8 days/floor	4 days/floor	7 days/floor
Construction duration	30 months	17 months	18 months	19 months
GFA exempted under JPNs/CFA	–	–	–	–

Table 4 Distribution of interviews and specific project-oriented questionnaire responses for case studies

Respondent	Interviews	Project-oriented questionnaire responses
Client/ Developer	25%	36%
Architect	35%	18%
Contractor	30%	36%
Others	10%	9%
Total	100%	100%
	20 interviews	11 questionnaires

and material use (Table 5). Most of these factors contribute to environmental, economic and social benefits.

As shown in Table 5, some benefits such as waste reduction and improved quality control were perceived as greater benefits in the project-oriented survey rather than in the industry survey (t-values $\leqslant -2.00$), indicating that prefabrication benefits might actually be greater in practice than generally expected by the building industry in Hong Kong. Similarly, the respondents' overall satisfaction level when using prefabrication was greater in practice when compared to the perceptions found in the industry survey (t-value$=-2.37 \leqslant -2.00$).

In the case study, the interviewees felt that additional inducements for adopting prefabrication methods in the selected projects were the incentive schemes provided by the government and the improved marketing image in demonstrating the use of environmentally friendly construction methods.

Economic benefits of using prefabrication

The results indicate that respondents' opinions are extremely divided on the cost of using prefabrication when compared to conventional construction. The disparity in the results shows that economic benefits are difficult to evaluate with off-site production (Blismas *et al.*, 2006; Goodier and Gibb, 2007). While the majority of respondents in the industry survey believe that the construction cost with prefabrication is about 20% more expensive than conventional construction, in the case studies, based on the limited data gathered, it was found that the average construction cost for prefabrication was only slightly higher (0.25% to 3%) than conventional construction. Previous research (Mak, 1998) showed that the cost of precasting is higher than in-situ construction by 10%–20%. However, some interviewees stated that reductions and savings in various other categories generally offset the slightly higher cost.

A recent study by Goodier and Gibb (2007) shows that the major advantages of offsite construction are the reduction of on-site construction time, the improved quality and the reduction of defects. With the exception of Project 5, the data indicated that construction time is significantly reduced by about 20% in projects adopting prefabrication and thus resulting in considerable savings (Table 8). Prefabrication contributes to less work completed on-site (e.g. external wall finishes, laying tiles and plastering) saving time at the later stage of the project, and avoids onsite construction delay due to local weather conditions. Prefabrication also permits early building enclosure and commencement of indoor works. Chu and Sparrow (2001) asserted that construction time reduction is also reflected in lower site overheads, less interest on loan repayments and early rental returns when prefabrication is used.

By adopting prefabrication, builders enjoy a shorter construction duration and lower labour requirement on site, both contributing to considerable savings in labour cost. In the case studies, the labour requirement is reduced on average by 16% and up to 30% in some projects. As precast components are produced off-site at a precast factory, fewer carpenters, steel reinforcement workers and plasterers are required on-site. Also, in Hong Kong, the precast factories are located in the Guangdong Province of China where both material and labour costs are lower (Chu and Wong, 2005).

Another economic benefit of using prefabrication found in the case studies is the improved quality and more rigorous quality control. While on-site output quality is highly dependent on the workmanship of construction workers and their supervision, in the case of prefabrication, quality is easier to control in a factory environment. Precast components are checked at the factory, which leads to not only significant reduction in defects on-site but also an improvement in the durability of components, thus resulting in considerable savings. Maintenance work and associated costs might also be reduced due to improved quality and durability (e.g. fewer instances of de-bonding tiles and water leakage risks).

Finally, the interviewees reported that gross floor area (GFA) exemption provided by government incentives schemes (Buildings Department, 2001, 2002) for the adoption of green features permitted the developers to gain one additional floor in most developments. In Project 2, GFA exemption accounted for about 10% of the total GFA. The economic benefits of these green features, therefore, are considerable.

Environmental benefits of using prefabrication

In the study, a variety of environmental benefits, namely material conservation and reduction in waste, air pollution as well as water consumption, were found.

The use of prefabrication techniques contributes to both material conservation and waste reduction. The respondents believe that waste reduction is the principal advantage of using precasting. The case studies show significant wastage reduction levels on construction sites

Table 5 Sampling distribution of the difference of means between industry survey and case study project-oriented survey

	Factors	Industry survey				Case study project-oriented survey				$\overline{x_1}-\overline{x_2}$	$\sigma_{\overline{x_1}-\overline{x_2}}$	t	$t_{Critical}$
		Rank	$\overline{x_1}$	S_{x1}	n_1	Rank	$\overline{x_2}$	S_{x2}	n_2				
Advantages of prefabrication	-Reduction of construction waste	2	3.90	0.89	83	1	4.75	0.43	8	−0.85	0.18	**−4.70**	−2.00 & 2.00
	-Improved quality control	1	3.98	0.82	83	2	4.75	0.43	8	−0.77	0.18	**−4.36**	
	-Improved on-site environmental issues: construction noise reduction	–	–	–	–	3	4.63	0.48	8	–	–	–	
	-Improved on-site environmental issues: construction dust reduction	–	–	–	–	4	4.63	0.48	8	–	–	–	
	-Improved health and safety	3	3.83	0.94	83	5	4.38	0.7	8	−0.55	0.27	**−2.03**	
	-Improved site management/ activities	8	3.48	1.00	83	6	4.25	0.66	8	−0.77	0.26	**−2.99**	
	-Reduction of construction time	5	3.69	0.77	83	7	4.13	0.93	8	−0.44	0.35	−1.26	
	-Reduction of material use	6	3.66	0.90	83	8	4.13	0.6	8	−0.47	0.23	−1.99	
	-Reduction of labour demand	4	3.71	0.84	83	9	4.13	0.78	8	−0.42	0.29	−1.43	
	-Improved productivity	7	3.51	1.02	83	10	4.13	0.78	8	−0.62	0.30	**−2.07**	
	-Reduction of programme time	10	3.36	1.05	83	11	4.00	0.87	8	−0.64	0.33	−1.95	
	-Improved ease of construction	9	3.39	0.94	83	12	3.63	0.70	8	−0.24	0.27	−0.88	
	-Project cost savings	11	3.22	0.98	83	13	2.38	0.70	8	0.85	0.27	**3.13**	
Limitations of prefabrication	-Site dimensions (narrow site)	2	3.62	1.11	82	1	4.00	0.71	8	−0.38	0.28	−1.36	−2.00 & 2.00
	-Lack of onsite storage area	–	–	–	–	2	4.00	0.00	7	–	–	–	
	-Not flexible enough	6	3.28	1.30	83	3	3.88	0.93	8	−0.60	0.36	−1.66	
	-Higher initial cost	1	3.81	1.08	83	4	3.63	0.86	8	0.19	0.33	0.57	
	-Site access	8	3.16	1.10	82	5	3.50	0.71	8	−0.34	0.28	−1.22	
	-Higher general cost	4	3.51	1.16	83	6	3.13	1.05	8	0.39	0.39	0.98	
	-Resistance to change	3	3.52	1.15	83	7	3.13	1.05	8	0.40	0.39	1.01	
	-Transportation	5	3.40	1.08	82	8	3.00	0.71	8	0.40	0.28	1.44	
	-Lack of in-house expertise	10	3.13	1.08	82	9	2.25	0.66	8	0.88	0.26	**3.36**	
	-Lack of suppliers	7	3.23	1.09	83	10	2.13	0.33	8	1.11	0.17	**6.61**	
	-Lack of industry expertise	9	3.13	1.08	83	11	2.13	0.93	8	1.01	0.35	**2.88**	
Satisfaction level of prefabrication	-Reduction of construction waste	1	3.83	1.08	82	1	4.50	0.50	8	−0.67	0.21	**−3.14**	−2.00 & 2.00
	-Overall satisfaction	2	3.67	0.82	84	2	4.38	0.70	8	−0.71	0.26	**−2.68**	
	-Delivery to site	6	3.45	0.92	83	3	4.13	0.33	8	−0.68	0.15	**−4.37**	
	-Reliability of product	3	3.64	1.07	84	4	4.13	0.60	8	−0.49	0.24	**−2.00**	
	-Monitoring/production techniques	5	3.51	0.94	83	5	4.00	0.71	8	−0.49	0.27	−1.81	
	-Design	9	3.16	0.99	83	6	3.88	0.93	8	−0.72	0.35	**−2.06**	
	-Final cost	8	3.25	0.88	83	7	3.75	0.66	8	−0.50	0.25	−1.98	
	-Reduction in construction time	4	3.54	0.99	84	8	3.75	0.83	8	−0.21	0.31	−0.67	
	-Material cost	7	3.28	0.85	83	9	3.63	0.70	8	−0.35	0.26	−1.30	
	-Communication with other members of the construction team	10	3.13	0.97	82	10	3.38	0.70	8	−0.25	0.27	−0.91	

Table 6 Sampling distribution of the difference of means between conventional and precast construction

Survey	Factors	Conventional Rank	$\overline{x_1}$	S_{x1}	n_1	Precasting Rank	$\overline{x_2}$	S_{x2}	n_2	$\overline{x_1}-\overline{x_2}$	$\sigma_{\overline{x_1}-\overline{x_2}}$	t	$t_{Critical}$
Industry survey (see Figure 1)	-Reduce waste	13	2.04	0.97	78	1	4.24	1.09	80	−2.20	0.16	**−13.41**	−1.96 & 1.96
	-Quality of end product	11	2.41	0.93	78	2	3.95	1.16	80	−1.54	0.17	**−9.22**	
	-Opportunity for standardization	12	2.40	1.07	77	3	3.92	1.25	79	−1.52	0.19	**−8.17**	
	-Site management	4	2.83	1.03	78	4	3.81	0.90	80	−0.98	0.15	**−6.36**	
	-Quality of design	3	2.95	1.06	78	5	3.73	0.87	80	−0.78	0.15	**−5.05**	
	-Aesthetic quality	8	2.63	0.99	78	6	3.70	0.97	80	−1.07	0.16	**−6.86**	
	-Programme progress	9	2.62	0.84	78	7	3.69	0.98	80	−1.07	0.15	**−7.37**	
	-Ease of maintenance	6	2.81	0.80	78	8	3.61	0.94	80	−0.80	0.14	**−5.77**	
	-Maximize returns	1	3.08	0.96	77	9	3.40	1.07	78	−0.32	0.16	**−1.96**	
	-Reduce material cost	7	2.71	0.99	78	10	3.39	1.28	80	−0.68	0.18	**−3.74**	
	-Life cycle of building	5	2.83	0.93	77	11	3.37	1.13	79	−0.54	0.17	**−3.26**	
	-Reduce overall project cost	2	3.06	0.90	78	12	3.31	1.20	80	−0.25	0.18	−1.43	
	-Partnership between companies	10	2.58	0.94	77	13	3.14	1.14	79	−0.56	0.17	**−3.35**	
Case studies project-oriented survey: advantages (see Figure 2)	-Reduction of construction waste	9	2.67	0.94	3	1	4.75	0.43	8	−2.08	0.56	**−3.70**	−2.262 & 2.262
	-Improved quality control	4	3.33	0.94	3	2	4.75	0.43	8	−1.42	0.56	**−2.51**	
	-Improved onsite environmental issues: construction noise reduction	11	2.67	0.94	3	3	4.63	0.48	8	−1.96	0.57	**−3.44**	
	-Improved on-site environmental issues: construction dust reduction	12	2.67	0.94	3	4	4.63	0.48	8	−1.96	0.57	**−3.44**	
	-Improved health and safety	7	3.33	0.47	3	5	4.38	0.70	8	−1.04	0.37	**−2.84**	
	-Improved site management/activities	8	3.00	0.00	3	6	4.25	0.66	8	−1.25	0.23	**−5.36**	
	-Reduction of construction time	2	3.33	0.90	3	7	4.13	0.90	8	−0.79	0.63	−1.25	
	-Reduction of material use	10	2.67	0.47	3	8	4.13	0.60	8	−1.46	0.34	**−4.23**	
	-Reduction of labour demand	13	2.33	0.47	3	9	4.13	0.78	8	−1.79	0.39	**−4.63**	
	-Improved productivity	6	3.33	0.47	3	10	4.13	0.78	8	−0.79	0.39	−2.05	
	-Reduction of programme time	3	3.33	0.94	3	11	4.00	0.87	8	−0.67	0.62	−1.07	
	-Improved ease of construction	5	3.33	0.47	3	12	3.63	0.70	8	−0.29	0.37	−0.79	
	-Project cost savings	1	3.67	0.47	3	13	2.38	0.70	8	1.29	0.37	**3.52**	
Case studies project-oriented survey: limitations	-Site dimensions (narrow site)	11	1.67	0.47	3	1	4.00	0.71	8	−2.33	0.37	**−6.31**	−2.262 & 2.262
	-Lack of onsite storage area	3	2.67	0.94	3	2	4.00	0.00	7	−1.33	0.54	**−2.46**	
	-Not flexible enough	2	2.67	0.94	3	3	3.88	0.93	8	−1.21	0.63	−1.90	
	-Higher initial cost	9	2.33	0.47	3	4	3.63	0.86	8	−1.29	0.41	**−3.17**	
	-Site access	1	1.67	0.47	3	5	3.50	0.71	8	−1.83	0.37	**−4.96**	
	-Higher general cost	4	2.67	0.90	3	6	3.13	1.00	8	−0.46	0.66	−0.70	
	-Resistance to change	5	2.33	0.47	3	7	3.13	1.05	8	−0.79	0.46	−1.72	
	-Transportation	10	1.67	0.47	3	8	3.00	0.71	8	−1.33	0.37	**−3.61**	
	-Lack of in-house expertise	7	2.00	0.00	3	9	2.25	0.66	8	−0.25	0.23	−1.07	
	-Lack of suppliers	6	2.00	0.00	3	10	2.13	0.33	8	−0.13	0.12	−1.07	
	-Lack of industry expertise	8	2.00	0.00	3	11	2.13	0.93	8	−0.13	0.33	−0.38	

Table 6 Continued

	Factors	Conventional				Precasting				$\overline{x_1}-\overline{x_2}$	$\sigma_{\overline{x_1}-\overline{x_2}}$	t	$t_{Critical}$
		Rank	$\overline{x_1}$	S_{x1}	n_1	Rank	$\overline{x_2}$	S_{x2}	n_2				
Case studies project-oriented survey: satisfaction level	-Reduction of construction waste	10	2.33	0.47	3	1	4.50	0.50	8	−2.17	0.32	**−6.69**	−2.262 & 2.262
	-Overall satisfaction	2	4.00	0.00	3	2	4.38	0.70	8	−0.38	0.25	−1.52	
	-Delivery to site	4	4.00	0.00	3	3	4.13	0.33	8	−0.13	0.12	−1.07	
	-Reliability of product	5	4.00	0.00	3	4	4.13	0.60	8	−0.13	0.21	−0.59	
	-Monitoring/production techniques	7	3.67	0.47	3	5	4.00	0.71	8	−0.33	0.37	−0.90	
	-Design	8	3.33	1.25	3	6	3.88	0.93	8	−0.54	0.79	−0.68	
	-Final cost	3	4.00	0.00	3	7	3.75	0.66	8	0.25	0.23	1.07	

when compared with conventional construction, with an average reduction of 65% and up to 70% in some projects. With prefabrication, timber formworks are avoided, saving precious space at the landfills. In addition, most of the trades generating waste on-site are conducted off-site at the manufacturing plant, where it is easier to reuse and recycle the waste generated. Reusable and recyclable steel formworks are used to cast the precast elements that also help avoid waste generation.

In the case studies, material conservation achieved by reducing timber formworks, plastering, tiling and concrete works is significant. As shown in Table 7, the quantity of saved timber was about 6.16 kg/m^2 of construction floor area (CFA) on average. The figures considerably vary from project to project. This is due to the difference in prefabrication percentages, the types of precasting (e.g. structural and volumetric precast components), the repetition levels and the number of floors/blocks. According to a recent study, timber formwork accounts for about 30% wastes identified in conventional construction sites, while wet trades and finishing works account for about 20% (Poon *et al.*, 2004). In the case studies, it is found that a reduction of plastering works (100%), tiling and concrete works (50%) are significant and contribute to waste reduction (Ng, 2002). Tam *et al.* (2005) have estimated that prefabrication in buildings contribute to waste reduction in plastering, timber formwork and concrete works by about 100%, 74%–87% and 51%–60% respectively. In the case studies it became clear that plastering works are avoided due to the high quality of concrete finish achieved with steel formworks. In addition, the tiling works are conducted in a factory environment resulting in less wastage, improved quality and durability, as well as reduced maintenance work and associated wastage during the operation phase. Quality control at the factory also permits easy identification of defects and rejection of unsuitable precast elements before they are transported to the site, resulting in less wastage on site arising from defects and rebuilt works.

In this study, air pollution reduction is examined on-site at the construction site, and off-site during the manufacturing process. According to the participants in the case studies, dust on-site is significantly reduced when adopting prefabrication. Prefabrication contributes to reductions of onsite construction activities and construction duration, thus reducing the nuisance factor faced by the nearby residents. The benefits are enhanced in dense urban environments such as Hong Kong, where sites are generally congested and surrounded by high-rise buildings. Moreover, pollution that occurs off-site during the manufacturing process is easier to control in a factory environment.

In the study, it was apparent that prefabrication contributes to a reduction in water consumption on-site, as elements are manufactured in a factory environment

Table 7 Material and cost savings of timber formwork by using prefabrication in selected projects

Project name	Timber formwork area saved (m^2)	Quantity of timber saved (t)	Timber saved/CFA (kg/m^2)	Timber material cost saved (HK$ million)[a]	Costs in US$ million	Timber disposal cost saved (HK$)[b]	Costs in US$	Total savings (HK$ million)	Costs in US$ million	Total savings/CFA (HK$/$m^2$)	Costs in US$
Project 2	7742.17	206.99	3.70	1.16	0.15	25 873.94	3317.17	1.19	0.15	21.18	2.71
Project 3	8617.76	224.31	11.83	1.29	0.17	28 038.33	3594.66	1.32	0.17	69.52	8.91
Project 5	9885.46	207.12	6.81	1.48	0.19	25 890.50	3319.29	1.51	0.19	49.53	6.35
Project 6	3461.78	72.85	2.34	0.52	0.07	9106.73	1167.53	0.53	0.07	16.99	2.18
Project 7	2620.45	58.12	6.11	0.39	0.05	7264.98	931.41	0.40	0.05	41.76	5.35
Total	32 327.62	769.39	–	4.84	0.62	96 174.48	12 330.06	4.94	0.63	–	–
Average	6465.52	153.88	6.16	0.97	0.12	19 234.90	2466.01	0.99	0.13	39.79	5.10

Notes: [a] Timber price in Hong Kong: HK$150/$m^2$; [b] disposal charge at landfills: HK$125/t; US$1=HK$7.8.

and wet trades (including tiling works) are avoided on-site. As mentioned above, plastering work is avoided due to the high quality concrete finish obtained with steel formworks. Project 2 achieved a 41% reduction of water consumption, due to prefabrication, dry construction system (hardiwall partition system), and recycling water treatment facility on-site.

Social benefits of using prefabrication

Improved site safety is found to be a major benefit of prefabrication when compared to conventional construction. Prefabrication contributes to a cleaner and safer working environment on-site, and safety control at the manufacturing plant is more efficient. Risks associated with working at height are avoided in the factory environment, thus improving workers' safety. Compared to the industry figures, the case studies show a significant reduction of accident rates (63% lower), with an average of 22 accidents per 1000 workers. Prefabrication also contributes to a reduction in construction noise and dust on-site, thus benefiting both the employees and the neighbouring communities. In addition, prefabrication improved quality and durability, tackling the maintenance problem of de-bonding tiles and eventually seems to ensure public safety.

Limitations of using prefabrication techniques in dense urban environments

Although the findings suggest that precast construction could bring significant benefits to the Hong Kong construction industry, the participants also expressed concerns about its application in dense urban environments. The industry survey respondents felt that higher initial cost and site dimensions (narrow site) were two major limitations of using prefabrication, followed by a

Table 8 Building performance for prefabricated building systems in the selected case studies[a]

Project name	Prefabrication percentage	Construction cost	Construction time	Labour requirement on-site	Accident rate/1000 workers	Construction waste
Project 2	60%	+0.25%	−20% 4 days cycle	−9.5%	30	−56%
Project 3	50%	+less than 2%	−20% 4–5 days cycle	−30%	4.5	−69%
Project 5	47%	+3%	+0% 8 days cycle	−15%	20	−70%
Project 6	70%	+0.3%	−20% 4 days cycle	−10%	34.6	–
Project 7	–	–	– 7 days cycle	–	–	–
Average	57%	+1.4%	−15% 5 days cycle	−16%	22.3 −63%[b]	−65%

Notes: [a] Data are gathered through interviews with project managers, architects and contractors in each project; [b] Comparison with industry figure in 2005 of 59.9 accident rate per 1000 workers.

natural resistance to change and higher general cost (Table 5). The respondents also thought that project costs were higher in prefabrication than conventional construction (t-value=3.13⩾2.00). The results from both surveys show consistency. In the project-oriented survey results, other limitations included the lack of flexibility and onsite storage areas, and site access (Table 5).

Economic limitations of using prefabrication

Although the findings suggest that prefabrication techniques provide significant economic advantages compared with conventional construction, participants in the study reported some economic limitations. As shown in Table 6, the higher initial cost is a major economic limitation in adopting prefabrication when compared with conventional construction methods (t-value=−3.17 ⩽−2.262). The higher initial cost is mainly due to the preliminary investment in a set of fabrication moulds (steel moulds). Chu and Sparrow (2001) also argued that precast construction could lead to higher cranage requirement resulting in higher costs. In the case studies, the respondents also mentioned that the transportation cost of prefabricated elements was higher when compared to conventional construction. For the case of Hong Kong, most prefabrication factories are located in the Guangdong Province of the People's Republic of China, which increases the overall transportation distance. A recent study (Goodier and Gibb, 2007) showed that life cycle costs should be used for the purposes of comparison. Many professionals in the current study, however, believed that by adopting a life cycle costing approach, the higher cost of prefabrication could be offset by other factors, such as reduction in construction time, labour requirement on site, and waste and resources reductions. One respondent also believed that by adopting more standardized component sizes across projects, the initial cost in steel mould fabrication could be reduced.

Environmental limitations of using prefabrication

Some respondents felt that the transportation of prefabricated elements and its associated pollution are environmental limitations when compared with conventional construction. One contractor mentioned that energy consumption is increased by 12% due to the transportation of the precast components. However, one respondent believed that within a life cycle approach, the air pollution on-site is significantly reduced as major building works are carried out off-site. In addition, air pollution is easier to control in a factory environment.

Social limitations of using prefabrication

One respondent argued that a wider use of prefabrication could pose serious social problems in Hong Kong. The reduction of labour requirement on-site as a result of using prefabrication techniques might increase the unemployment rate in the building industry, and affect the economy of Hong Kong, as most prefabrication factories are located in the Guangdong Province. A recent study (Tam, 2002) demonstrated that a wider use of prefabrication could cause a 43% reduction in site labour requirement.

Other aspects

The results show that small site dimensions (narrow sites), the lack of on-site storage area, site access and transportation are critical when using prefabrication in dense urban environments. With the adoption of the just-in-time delivery principle, storage area on-site can be kept to a minimum (Chu and Wong, 2005). In Project 5, the storage area for prefabricated elements accounted for about 50% of the typical floor area. In the case studies, site access for large precast elements seemed to be an issue due to traffic congestion and narrow access roads.

Other limitations with the use of prefabrication reported by the interviewees are the need for early decisions in the design and building process, and the resistance to change typical in any industry. Early collaboration between the designers and the contractor is required, as elements are fabricated off-site before construction starts. This also implies a lack of flexibility in allowing late design changes to meet market needs.

Comparison between prefabrication and conventional construction

One of the objectives of this study was to compare the use of precast and conventional construction methods in buildings in Hong Kong. In both surveys, the results show consistency. The respondents were requested to assign an appropriate rating on a scale of 1 to 5, from the highest to the lowest level, against each factor to reflect the importance of the factors. As presented in Figures 1 and 2 and Table 6, the respondents believe that waste reduction and end product quality were the most important considerations when using prefabrication whereas these considerations were the least important in conventional construction as indicated by the industry survey. The respondents reported that maximization of returns was the most important consideration in conventional construction, followed by reduction of overall project cost and design quality.

In the industry survey (Table 6), the results demonstrate that there are significant differences between the mean values for prefabrication and conventional construction for all factors with the exception of 'reduce overall project cost' (t-value=−1.43⩾−1.96). Also, in the project-oriented survey, 'project cost savings' was considered as a greater advantage when using conventional construction compared to the use of prefabrication techniques (t-value=3.52⩾2.262). For most factors, the mean values for the prefabrication method are higher than those of the conventional method (t-values ⩽ −1.96 and −2.262), showing improvement. The waste reduction factor demonstrates the highest significance when calculating differences between means (t=−13.41), and is considered the greatest benefit of using prefabrication.

Building performances and material savings in the selected projects adopting prefabrication

In the case studies, the building performance data were gathered through interviews with the project manager, the architect and the contractor in each project. As shown in Table 8, the prefabrication percentages (by volume) for the five case studies were on average about 57%. The construction cost for prefabrication was slightly higher than for conventional construction method (on average 1.4% higher). The average construction time and labour requirement reduction achieved on-site were about 15% and 16%, respectively. The average accident rate was low, about 22.3 per 1000 workers. Construction waste generation on site was also reduced by about 65% on average. As presented in Table 7, the amount of timber saved by avoiding the use of timber formworks in the five developments was considerable, with an average of 6.16 kg/m^2 of CFA. This contributed to significant savings in material and waste disposal costs.

Conclusion

The study aimed to assess the sustainable construction aspects of prefabricated high-rise buildings in the dense urban environment of Hong Kong. The study shows that the improved quality control, improved environmental performance (reduction of waste, dust and noise), improved site safety, the reduction of labour demand and construction time are significant benefits when adopting prefabrication. In the case studies, on average, a reduction of 65% of construction waste, 16% of labour requirement on-site and 15% of construction time was noted when adopting prefabrication. The accident rate was on average 63% lower than the industry figure. The findings also revealed that the construction cost was slightly higher than conventional construction when adopting precasting (+1.4% on average). However, this was offset by a reduction of site activities and construction time (less on-site finish work with prefabrication), as well as improved quality and environmental performances. As far as limitations are concerned, the major limitations of using prefabrication in a dense urban environment included the higher initial cost, site dimensions (narrow site), site access, and the lack of storage area on-site for prefabricated elements. However, these limitations could be overcome.

In conclusion, this study, through a variety of data, has showed that a wider application of prefabrication in buildings in Hong Kong could significantly contribute to economic, environmental and social benefits, especially in dense urban environments. The aspiration towards a more environmentally responsible and sustainable building industry is critical to achieve a healthy built environment and efficient use of resources.

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