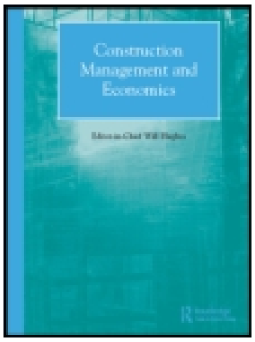

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Design issues of using prefabrication in Hong Kong building construction

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Prefabrication techniques have been adopted for the last two decades in public housing projects in Hong Kong, but the use of prefabrication in the private sector was encouraged only after the implementation of the Joint Practices Notes which promote its use. Although previous studies acknowledge the environmental benefits of using prefabrication, only a few studies have addressed sustainable design concepts (closed-loop) in the adoption of precast construction. A questionnaire survey was administered to experienced Hong Kong construction professionals, and case studies of recently completed building projects were compiled to ascertain the use of prefabrication with reference to life cycle approach. The findings revealed that prefabrication, combined with modular design and standard components, saved time and construction/design costs, as buildings systems were used across projects. However, in some projects, specific site conditions restricted the use of similar prefabricated building systems across projects. Surprisingly only a few participants addressed life cycle design concepts such as design for deconstruction when adopting precast construction. Also, although it is common knowledge that flexible and demountable prefabricated building systems would result in efficient use of resources, their use is seldom practised in Hong Kong.

Keywords: Hong Kong, life cycle design, prefabrication, precast concrete, sustainable construction.

Introduction

Prefabricated buildings system

Prefabrication is a manufacturing process that takes place at a specialized facility, where various materials are joined to form a component part of the final installation (Construction Industry Research and Information Association, 1999). In the construction industry, prefabrication is the first degree of industrialization, followed by mechanization, automation, robotics and reproduction (Richard, 2005). Industrialization is based on quantity in which large-scale production of elements reduces the costs. Although nowadays most components used in buildings are industrialized, the construction industry still relies on in-situ conventional construction methods which are not only labour intensive, but also a source of pollution and nuisance such as dust, noise, muddy site run-off, and considerable amounts of construction waste (Construction Industry Review Committee, 2001). Timber formwork accounts for about 30% of wastes identified in conventional construction, while wet trades and finishing works account for about 20% (Poon *et al.*, 2004). Additionally, onsite quality control is slack at best. Built products are rarely defect-free as quality control is less efficient than in a factory environment (Construction Industry Review Committee, 2001). It is recognized that prefabrication can substantially reduce most of the problems associated with conventional construction. Indeed industrialized building systems can simplify the construction process as the design and construction are not re-created for each new project. When building systems are industrialized, flexible and demountable (IFD), total or partial demolition of a building can be avoided, thus contributing to the sustainability agenda (Richard, 2007). This is a significant issue, especially in a dense and compact urban environment such as Hong Kong, where available space is limited for construction waste disposal.

Sustainable construction and prefabrication

For the last two decades, sustainable development and sustainable construction have been of increasing

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concern throughout the world (World Commission on Environment and Development, 1987; Conseil International du Batiment, 1998, 1999; Bourdeau, 1999; Sjostrom and Bakens, 1999). Sustainable construction is 'the creation and responsible management of a healthy built environment based on resource efficient and ecological principles' (Kibert, 1994, pp. 3–12). The construction industry is a key component of socio-economic development in most countries, and therefore it plays a major role in ensuring sustainable development (United Nations Environment Programme, 2003). It is also recognized that the construction industry and buildings are major users of resources (including non-renewable ones) in terms of energy and materials. In the USA, buildings consume about 37% of total energy, 68% of all electricity and 40% of raw material used (United States Green Building Council, 2003). Indeed construction activities have significant and irreversible effects on the environment, such as contributing to air and water pollution, and waste generation.

Prefabrication has been identified as a solution to reduce waste generation during the building design and construction processes (Poon and Jaillon, 2002; Osmani *et al*., 2006; Jaillon and Poon, 2008; Jaillon *et al*., 2009). Still, a large amount of construction waste is produced at the end of a building's lifespan. Schultmann and Sunke (2007), based on a life cycle energy analysis, suggested that considering the limited space available for the disposal of waste, the depletion of resources such as wood, metal and natural gravel, the escalating amount of resource consumption for the manufacturing of new construction materials and emissions released into the environment, sustainable construction should encompass closed-loop material flows, so that deconstructed materials are redirected into the material flow. To achieve this aim, the building industry will require a fundamental modification in the way buildings are designed, constructed and used. According to Schultmann (2005) the design of a building would significantly influence the amount of potentially reusable/recyclable materials at the end of the useful life of a building. Kibert (2005) has suggested that the fundamental rules for a closed-loop building materials strategy include: (1) buildings must be deconstructable; (2) products must be disassemblable; (3) materials must be recyclable; (4) products/materials must be harmless in production and in use; and (5) materials dissipated from recycling must also be harmless. These rules ensure that building materials can be recovered and reused at the end of the building's life. The building material cycle is closed and the goal is to be waste-free. Design for deconstruction in buildings may significantly reduce waste generation and divert waste away from landfills (Kibert, 2003). In applying design for deconstruction principles, the connections between elements are essential. Indeed, the use of mechanical connections rather than chemical ones is highly recommended (Crowther, 2002, 2005). Through a review of the construction industry, Te Dorsthorst and Kowalczyk (2005) also agreed that the details of construction and deconstruction are essential, and similarly critical are aspects of standardization of building elements in terms of size, like length and height, to facilitate the building reuse. According to Crowther (2002, 2005) the design of joints and connectors should withstand repeated use, and the separation of the structure from the cladding, internal walls and services is essential. The term 'open building system' is well known and defines the principles of ordering and combining subsystems by which interference between subsystems is minimized (Kendall and Teicher, 2000; Yashiro, 2003). Previously, Habraken (1972) in a seminal book, *Supports: An Alternative to Mass Housing*, suggested the separation of the 'support' (building base) from the 'infill' (fitting out) in the design and construction of residential buildings to encourage the participation of inhabitants in the design process.

In the literature, the development of industrialized, flexible and demountable (IFD) building systems in the Netherlands is well known (Van Gassel, 2002; Quah *et al.*, 2004; Richard, 2006). In the IFD building systems, flexible refers to possible changes in design layout over time (based on users' requirements), and demountable refers to the disassembly of components for repair or reuse in another location or form (Quah *et al.*, 2004). Dry-joints are necessary to achieve IFD building systems. In the Netherlands, demountable precast concrete systems have been used for the last two decades in various buildings such as office buildings, schools and hospitals (Vambersky, 1988, 1994). Reinhardt introduced the concept of demountable buildings in the Netherlands in 1976, promoting the use of demountable connections with precast concrete building systems. Three systems were developed, namely, the Bestcon 30 system, the CD20 system (slabs and columns system only) and the Matrixbouw system (Vambersky, 1988, 1994; Fédération Internationale du Béton, 2008). The systems consisted of standard precast columns and floors series which are bolted in place after assembly (Addis and Schouten, 2004). Another system also used in the Netherlands and named the MX-5-method consisted of concrete walls, columns and floors bolted together, thus ensuring that they are demountable for possible reuse (Te Dorsthorst and Kowalczyk, 2005). Addis and Schouten (2004) have recommended for precast concrete beams and columns connection, the use of steel and fixings and bolted connections in preference to cast-in-situ connections that require grouting to allow deconstruction. They also stated that an in-situ concrete structure might be suitable only for recycling since it is difficult to dismantle without its destruction, and therefore recommend the use of precast concrete elements.

NEXT21 (Osaka Gas, 2000), an experimental housing project in Japan, has demonstrated flexible, adaptable and demountable building concepts to promote sustainable design. The highly flexible architectural system provides flexible layout of internal partitions, building services as well as external walls. The structure has a long lifespan, and the infill, cladding and piping systems are flexible and can be modified easily, thus responding to individual users' requirements over time.

Life cycle is an important issue that is well documented in the literature (McDonaugh and Braungart, 2002; Kotaji *et al.*, 2003; Anderson *et al.*, 2009). However, few studies consider life cycle assessment (LCA) and life cycle costing (LCC) for high-rise precast buildings located in dense urban environments (Hong Kong Housing Authority, 2002). In addition, LCA generally assesses building components and materials during their whole life cycle, but design is more difficult to assess.

Design issues concerning the use of precast construction in Hong Kong

In Hong Kong, not only do most of the construction activities still rely on traditional in-situ construction methods which fail to abide by the sustainable construction goals by polluting, but these activities also lack stringent quality control. The Construction Industry Review Committee report (2001) provided recommendations for improving the performance of the construction industry. Among these recommendations, the Construction Industry Review Committee proposed a wider use of standardized and modular components in local construction, as well as a wider adoption of prefabrication. The report also advocated the consideration of life cycle costs, buildability, maintainability, reparability, upgradeability and durability early in the design process to improve the environmental performance of a project and reduce the generation of demolition waste. Subsequently, the Hong Kong government initiated incentive schemes in 2001 and 2002, through the Joint Practice Notes 1 and 2 (JPNs 1&2), promoting the use of green building technologies and prefabrication (Buildings Department, 2001, 2002). Under the schemes, a financial incentive in the form of gross floor area (GFA) exemption is granted for buildings adopting green features such as prefabricated non-structural external walls. In addition, the government has issued a code of practice for the use of precast concrete construction (Buildings Department, 2004).

Since 1996, sustainable design and construction is assessed by using the Hong Kong Building Environmental Assessment Method (HK-BEAM). HK-BEAM (Building Environmental Assessment Method, 2004) is a rating system (voluntary scheme) for the evaluation of environmental aspects of building performance over the whole life cycle of a project. The environmental aspects cover site characteristics, material attributes, energy use, water use, indoor environmental quality, innovations and additions. As far as materials for new buildings are concerned, the criteria cover and advocate the use of prefabrication, modular and standardized design, flexibility and durability in buildings. Credits are awarded where criteria are met and add up to a final score corresponding to an overall assessment grade.

A few studies have examined the environmental benefits of prefabricated buildings in the private sector (Fong *et al.*, 2003; Jaillon and Poon, 2008), and assessed the waste reduction on site by using prefabrication (Tam *et al.*, 2005, 2007a; Jaillon *et al.*, 2009). Fong *et al.* (2003), through a case study analysis, not only demonstrated a reduction of 56% of construction waste by using prefabrication but also recorded reductions in water consumption (41%) and construction time (20%). Although a groundbreaking study, it was confined to only one building sample using innovative precast techniques. By reviewing the use of prefabrication in Hong Kong, Tam *et al.* (2005) suggested that the use of prefabrication reduced waste arising from timber formwork and concrete work. However, a possible shortcoming of this research may be the definition of wastage level. They defined wastage level as the remains of delivered materials after being used in the built work that included surplus materials that may be reused in other projects.

In the public sector, where prefabrication has been used for the last two decades, the construction of public housing combines prefabrication and standard modular design (Mak, 1998; Chan and Chan, 2002). Precast concrete components used in public housing projects generally include standard precast façades, staircases, beams, internal partitions and semi-precast slabs. Recently completed projects include innovative precast components such as volumetric bathrooms and kitchens (Chiang *et al.*, 2006; Tam, 2007). However, in contrast to overseas literature, in Hong Kong there are only a limited number of studies on design concepts to promote the reuse and recycling of prefabricated buildings at the end of their life cycle (closed-loop).

This article, therefore, seeks to bridge some of the knowledge gaps in design issues, and to promote a life cycle approach, when using prefabrication. The objectives of the paper are to: (1) examine the present industry practices and the views of building professionals (architects, engineers and contractors) regarding design aspects of using prefabrication in dense urban environments; (2) compare design concepts adopted in conventional and prefabrication construction in buildings in Hong Kong; (3) discuss design issues of using prefabrication to promote a life cycle approach.

Research method

The findings delineated in this paper have been obtained from an industry questionnaire survey, seven detailed case studies, face-to-face interviews with building professionals and site observations. The industry questionnaire survey aimed to investigate the perspective of the construction industry in general regarding the use of prefabrication, design issues and sustainable construction. The industry questionnaire survey covered a large sample of building professionals to provide representative views of the industry participants. The case studies attempted to gather data regarding the present practices of the industry in using prefabrication in high-rise buildings which also promotes a life cycle approach. The case studies provided information based on actual details of building projects as well as precise quantitative data of existing industrial practices. The case studies also included face-to-face interviews and site observations to validate the data collected. The site observations covered events in real time and context as well as showing the follow-up of progress and different stages of construction.

For the industry survey, a questionnaire was developed from key issues identified in the literature and further enhanced with ideas from preliminary interviews with professionals in Hong Kong. A pilot survey was conducted with experienced building professionals to amend the final version of the questionnaire. The questionnaire was then administered by e-mail to 354 building professionals from registered companies and government departments. There were 84 respondents mainly from experienced engineers (28%), architects (21%) and builders (18%) from private and government sectors. The response rate was 24%, with individual responses rates for architects, contractors and engineers of respectively 10%, 18% and 43%. In the questionnaire (relevant questions are shown in Tables 3 to 6), the respondents were requested to rate on a scale of 1 to 5, from the highest to the lowest level, each factor to ascertain the perceived importance of the factors included in each question. For each factor, the mean was calculated based on weightings from (–2) being 'least important' to (+2) being 'most important'. The questionnaire was specifically devised to allow a comparison between prefabrication and conventional construction methods. 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. The comparison in construction methods was also discussed during the face-to-face interviews. Similar methods were applied to compare the responses from the architects, engineers and contractors.

Face-to-face interviews were conducted with 35 building professionals involved in the selected case study projects and with the respondents of the industry questionnaire survey in order to further validate the collected data. Interviews were conducted individually or in small groups of professionals involved in the same project. However, some professionals were interviewed more than once to gather additional data. The building professionals interviewed included clients, architects, project managers, structural engineers, contractors and manufacturers of precast components. A standard list of questions was prepared using similar topics to the industry survey. The questions included: (1) reasons for using/not using prefabrication in the project; (2) benefits and limitations of using prefabrication; (3) comparison with conventional construction; (4) design aspects of using prefabrication; and (5) design and life cycle aspects when adopting precast construction. In addition, site observations were conducted at six construction sites and one precast element manufacturing plant. The building site visits revealed the present industry practices of prefabrication and its application in dense urban environments whereas the visits at the manufacturing plant focused on precast manufacturing techniques and processes.

Additionally, five residential as well as non-residential projects using prefabrication in Hong Kong, and two developments using conventional construction were selected as case studies. The selection criteria for the case studies included building types and height, year of completion (i.e. selection of recently completed projects), project size, and different design characteristics. The design characteristics analysis consisted of (1) standard/non-standard block design; (2) modular precast structural grid; (3) variations of layout or repetition at every floor; (4) symmetry or rotational symmetry in a block layout; (5) repetition on more than one block; and (6) the use of life cycle design concepts (e.g. design for deconstruction (DfD) and IFD building systems) when adopting prefabrication in the projects. The seven projects are described in Tables 1 and 2. Drawings and project documentation were collected from the architects, clients, contractors and the Buildings Department.

Table 1 Details of institutional building projects using conventional construction and prefabrication

	Conventional construction	Precast construction	
	Project 1	Project 2	Project 3
Project description	One 14-storey tower 3-level podium	One 17-storey tower 3-level podium	Two 14-storey towers
Year of construction	2003–05	2005–07	2006–07
Site area (m^2)	3500	4386	3950
CFA (m^2)	30 821	30 404	37 424
Precast % (by volume)	–	47%	40%
Type of prefabricated elements	GRC panel	• Semi-precast slab • Precast beam & column • Precast staircase • Precast façade	• Semi-precast slab • Precast beam • Precast staircase
Design characteristics	• Non-standard block design • Little symmetry due to small site area	• Non-standard block design • Modular precast structural grid (8.4m × 8.4m) • Variations of layout on each floor	• Non-standard block design • Similar modular precast structural grid from Project 2 • Variations of layout on each floor • Rotational symmetry

Results and discussion

Design issues concerning the use of prefabrication in dense urban environments

In the industry survey, the respondents were asked to rate the benefits and limitations of using prefabrication in buildings located in dense urban environments, thus reflecting the importance of each factor. Some factors have direct impact while others may indirectly affect design issues when prefabrication is adopted. As shown in Table 3 and Figure 1, in the industry survey, the building professionals agreed that one of the major benefits of using prefabrication was the 'improved quality control'. However, significant difference between the means from the architects', the engineers' and the contractors' responses were noted (Table 3). Architects felt that the 'reduction of programme time' and 'reduction of design time' were less important benefits when using prefabrication but engineers and contractors assigned higher importance to these factors. The benefits of using prefabrication in dense urban environments have been previously discussed by the authors (2008).

While the industry survey results indicated significant advantages of using prefabrication, the respondents also expressed concerns regarding applying prefabrication in Hong Kong. Some limiting factors seemed to exert direct or indirect impacts on the perceptions of different stakeholders. As shown in Table 3 and Figure 2, surprisingly, the architects ranked the 'lack of in-house expertise' and 'lack of industry expertise' as major limitations. The 'increase of design time' by using prefabrication was seen by the architects as a major obstacle in using prefabrication whereas the contractors and the engineers expressed contradictory opinions. Additionally, as opposed to the architects' responses, contractors and engineers believed that 'site access' was an important limitation of using prefabrication in dense urban areas. The engineers also ranked 'transportation' as important impediment to the use of prefabrication (third ranking). However, there is a common view among the respondents that 'site dimensions (narrow site)' might indeed be a major limitation on the use of prefabrication techniques in dense urban environments. The respondents also agreed that the 'repetitive design leading to monotony', the 'design process', 'not design led', 'poor connection with other elements' and the 'poor quality image' were negligible impediments to the use of prefabrication. In the case studies, the respondents expressed more practically oriented apprehensions about the adoption of prefabrication and indicated that the 'lack of onsite storage area' and the lack of flexibility were the major problems when using prefabrication.

Site storage and access

In the case studies, the average storage area for prefabricated components accounted for about 22% of typical floor areas. In Project 3, which used a precast building system that was very similar to that of Project

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

	Conventional construction	Precast construction		
	Project 4	Project 5*	Project 6*	Project 7
Project description	Eight 35-storey towers providing 1404 units	Five 41-storey towers providing 3533 units	Six 40-storey towers providing 4500 units	Two 48-storey towers & 2-level podium, providing 442 units
Year of construction	2002–04	2005–07	2006–08	2001–03
Site area (m^2)	NA	NA	35 000	5714
CFA (m^2)	119 900	158 741	NA	56 000
Precast % (by volume)	0%	34%	NA	60%
Type of prefabricated elements	–	• Precast façade • Semi-precast slab (100% of floor area) • Precast staircase • Precast beam • Precast landing • Precast refuse chutes • Precast internal partition	• Precast façade • Semi-precast slab • Precast staircase • Precast beam • Precast refuse chutes	• Precast staircase & façade • Lost form panels • Semi-precast balcony • Dry wall system
GFA exempted under Jens/CFA	–	–	–	10%
Design characteristics	• Non-standard block design • Repetition on more than one block • Repetition on every floor • Symmetry in block layout	• Standard block design • Standard precast components • Repetition on more than one block • Repetition on every floor • Symmetry in block layout	• Non-standard block design with modular design • Standard precast concrete components (use in Project 5) • Repetition on every floor • Rotational symmetry in block layout	• Non-standard block design • Non-standard precast concrete components • Repetition on more than one block • Repetition on every floor • Symmetry in block layout

Notes: * Public housing projects. NA: not available.

Table 3 Advantages and limitations of using prefabrication techniques (industry survey results): opinions of architects, contractors and engineers**

	Factors	Architects' responses (n = 18)			Contractors' responses (n = 15)			Engineers' responses (n = 23)		
		Mean	Standard deviation	Rank	Mean	Standard deviation	Rank	Mean	Standard deviation	Rank
Advantages of using prefabrication	Improved quality control	1.17	0.76	1	0.93	0.77	1	1.00	0.72	3
	Reduction of construction waste	1.17	0.90	2	0.93	0.68	2	1.04	0.86	2
	Improved health and safety	1.17	0.83	3	0.67	0.87	3	1.09	0.78	1
	Reduction of material use*	1.06	0.85	4	0.53	0.62	8	0.65	0.87	8
	Reduction of labour demand	0.83	0.76	5	0.53	0.88	7	0.96	0.62	4
	Improved productivity	0.72	0.56	6	0.47	1.26	10	0.74	0.85	7
	Improved site management & activities	0.72	0.8	7	0.60	1.20	5	0.35	0.76	10
	Reduction of construction time	0.67	0.75	8	0.67	0.70	4	0.87	0.99	5
	Improved ease of construction	0.50	0.76	9	0.47	1.20	11	0.43	0.71	9
	Project costs savings	0.17	0.90	10	0.60	0.71	6	0.26	0.85	12
	Reduction of programme time*#	–0.11	0.99	11	0.53	0.72	9	0.83	0.96	6
	Fast return on investment∧	–0.12	0.83	12	–0.33	1.07	13	0.35	0.70	11
	Reduction of design time*#	–0.89	0.87	13	0.20	0.83	12	–0.26	0.85	13
Limitations of using prefabrication	Lack of in-house expertise#	0.83	0.96	1	0.33	1.14	9	–0.04	0.95	14
	Lack of industry expertise	0.67	0.94	2	0.40	1.14	7	0.17	0.96	12
	Higher initial cost	0.56	1.17	3	1.00	0.82	1	1.04	0.86	1
	Increase of design time	0.56	0.90	4	–0.20	1.28	13	0.13	1.12	13
	Site dimensions (narrow site)	0.50	1.17	5	0.87	1.09	2	0.87	0.80	2
	Resistance to change	0.39	1.11	6	0.73	0.93	4	0.52	1.14	7
	Transportation	0.33	1.25	7	0.40	0.71	6	0.78	0.98	3
	Higher general cost	0.28	1.15	8	0.80	1.05	3	0.65	0.96	5
	Lack of suppliers	0.22	1.13	9	0.33	0.94	8	0.43	1.14	8
	Not flexible enough∧	0.17	1.21	10	–0.13	1.26	12	0.70	1.08	4
	Repetitive design leading to monotony	0.17	1.07	11	–0.20	1.05	14	0.26	0.67	10
	Design process	0.06	0.91	12	0.07	1.06	10	0.22	0.88	11
	Site access	0.00	1.11	13	0.47	0.88	5	0.57	0.88	6
	Not design led∧	–0.22	1.23	14	–0.67	0.94	16	–0.04	0.95	15
	Poor connection with other elements	–0.33	1.11	15	0.00	1.32	11	0.30	1.20	9
	Poor quality image	–0.56	1.17	16	–0.4	1.31	15	–0.39	0.87	16

Notes:
* Significant difference between the means from architects' and contractors' responses.
# Significant difference between the means from architects' and engineers' responses.
∧ Significant difference between contractors' and engineers' responses (*t critical:* –2.021 & 2.021).
** Question asked: Do you agree the following are advantages/limitations when using precast concrete in Hong Kong building projects? 1 = Strongly disagree; 3 = Neutral; 5 = Strongly agree.

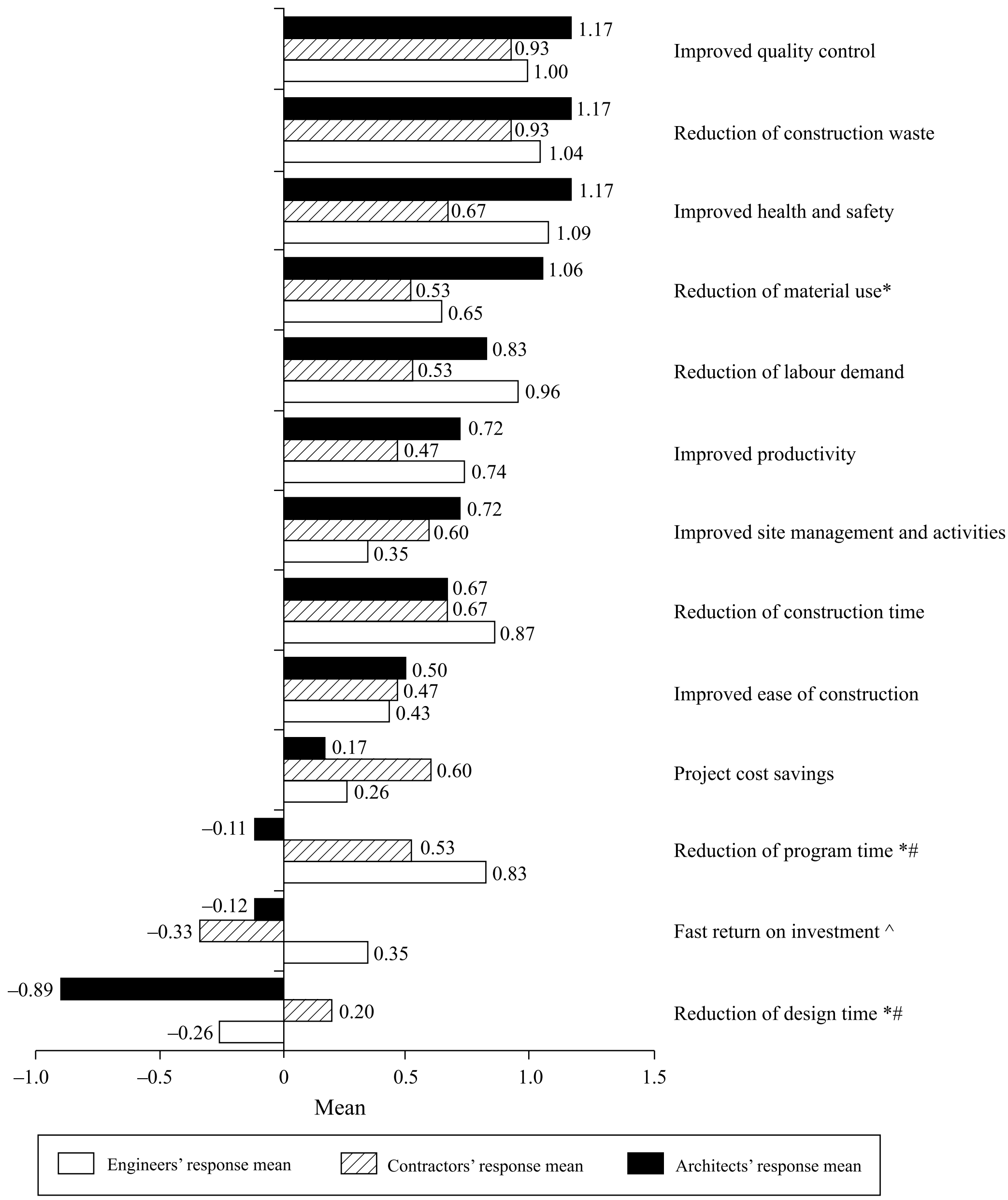


Figure 1 Benefits of using prefabrication techniques: responses from architects, contractors and engineers (industry survey results)
Notes: *Significant difference between the means from architects' and contractors' responses. #Significant difference between the means from architects' and engineers' responses. ^Significant difference between contractors' and engineers' responses. *t critical:* –2.021 & 2.021.

2, the small site area impeded the use of precast columns. In fact, the ratio of storage area and typical floor area in Project 3 was seven times smaller than the area in Project 2. In Project 2, the precast columns were stored in a vertical position in an open space area of the site, and required a storage area of 25 square metres (5 × 5 metres) and a height of at least 3 metres. Chu and Wong (2005) argued that the storage areas for precast components could be kept to a minimum by adopting just-in-time delivery. Additional practical difficulties were expressed including site access and transportation. In fact, precast components are generally transported by trucks from the factory to the construction site, thus transportation plays a major role in determining the dimensions of prefabricated elements.

Required design time

The 'increase of design time' by using prefabrication was perceived by the architects as a major limitation.

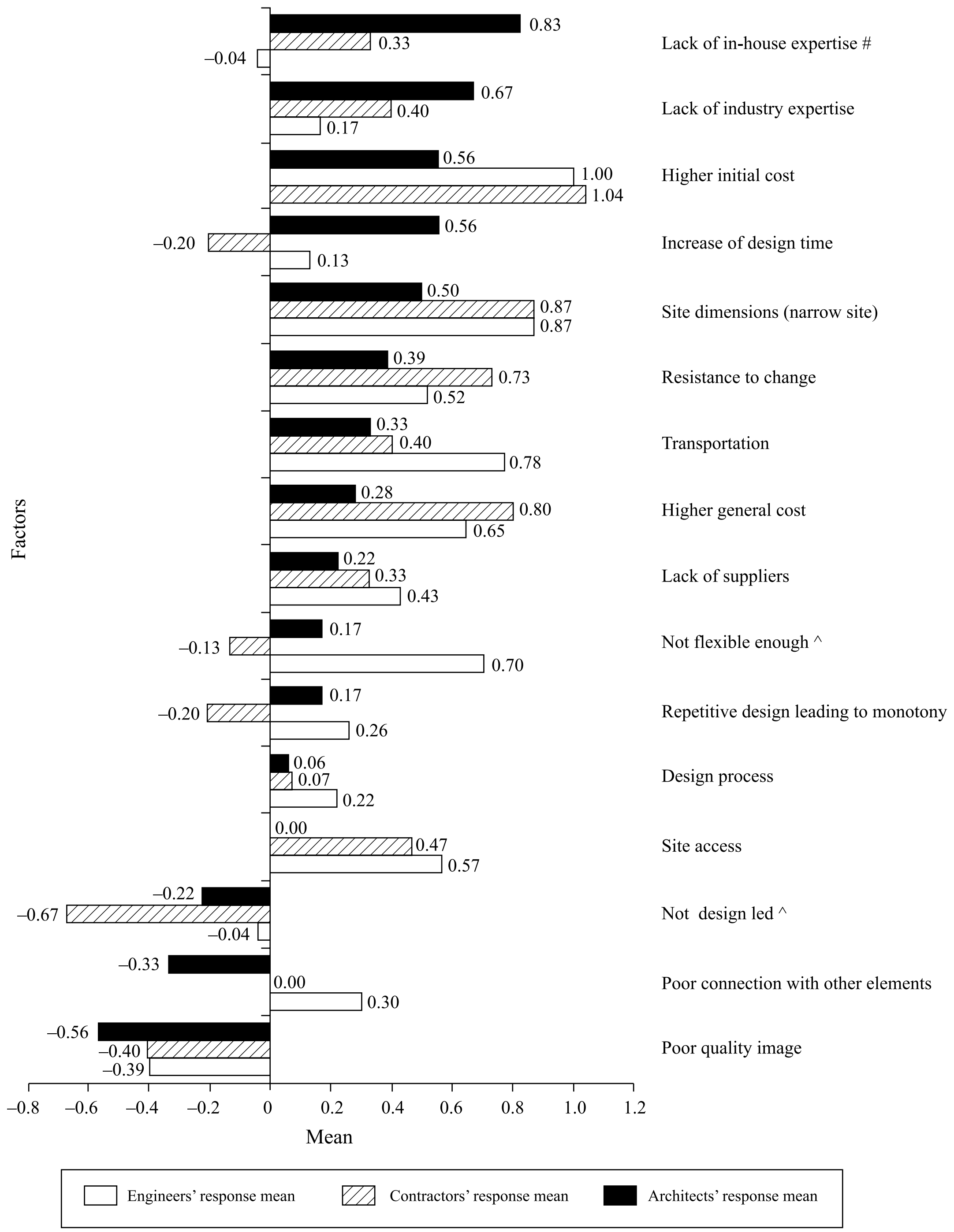


Figure 2 Limitations of using prefabrication techniques: responses from architects, contractors and engineers (industry survey results)

Notes: *Significant difference between the means from architects' and contractors' responses. #Significant difference between the means from architects' and engineers' responses. ^Significant difference between contractors' and engineers' responses. *t critical:* –2.021 & 2.021.

The design process, when using prefabrication, is an interactive process that requires early collaboration between architects, contractors and manufacturers. In addition, the building layout of private developments in Hong Kong is generally non-standard and varies from one development to another. The prefabrication system is, therefore, reinvented for each new project. Time is also required in the design process to develop new designs and build one-to-one scale mock-ups at the factory, such as in Project 2. However, the contractor in Project 3 believed that when similar prefabricated building systems across projects are adopted, the reduction in design time is considerable.

Flexibility

Finally, the lack of flexibility was also perceived by the respondents as a major limitation of using prefabrication. The respondents opined that late design modifications to meet market needs were not possible with prefabrication. Early decisions to finalize the building design are required with prefabrication as precast components are produced before construction starts. The findings match the issues discussed by Tam *et al.* (2007a) who have confirmed, by using a questionnaire survey with building professionals, that inflexibility in respect of design modifications and higher initial construction cost are the major barriers to the application of prefabrication in Hong Kong.

Comparison between prefabrication and conventional construction

In the industry survey, the respondents were asked to assign rating to design issues when using prefabrication or conventional construction, thus reflecting the importance of each factor. As shown in Table 4, there is a common view among the respondents, including architects, engineers and contractors that the 'quality of end product' and the 'opportunity for standardization' were the most important design issues in adopting prefabrication. The results demonstrate that there are significant differences between the mean values for prefabrication and conventional construction for all factors with the exception of 'quality of design' in the architects' responses (t value = $-1.26 \geq -2.021$) and in the engineers' responses (t value = $-1.79 \geq -2.021$), as well as the 'ease of maintenance' in the contractors' responses (t value = $-0.89 \geq -2.056$). For most design factors, the mean values for prefabrication are higher than those of the conventional method (t values ≤ -2.021 and -2.056), showing enhancement.

Higher quality

The findings confirmed that prefabrication techniques generally contribute to higher quality of end products. Prefabrication leads to higher quality control, due to improved supervision at the factory and advanced manufacturing technologies. Precast elements are rigorously checked and tested at the factory, reducing defects associated with onsite work. The higher quality of products achieved with prefabrication (e.g. fewer risks of water seepage and de-bonding of tiles), results in an improvement in the durability of the components and a reduction in maintenance works and associated costs as well as waste generation. In Project 7, the project manager asserted that no water seepage was reported by the occupants after the completion of the building. In addition, precasting techniques allow a better positioning and coverage of the reinforcement bars in precast components thus reducing the risks of corrosion (Dana, 2006). In the case studies, the high quality concrete finish achieved with steel formworks helped circumvent the need for plastering works. In Project 2, the architect adopted bared-face precast column finishes, thus reducing material consumption. Once again, similar findings are reported by Tam *et al.* (2005) who have estimated that prefabrication in buildings contributes to material savings in plastering and timber formwork by about 100% and 74%–87% respectively.

Standardization

Additionally, as presented in Tables 4 and 5, opportunities for standardization are greater when adopting prefabrication. In Table 5, 'repetition of similar precast elements at every floor' and 'standard modular design' were the most important design factors when adopting prefabrication in buildings. Precast elements are generally cast by using steel moulds that are more expensive than traditional timber formworks. Repetition of precast elements is a requirement to achieve economy of scale in one project. Moreover, with standardization, precast manufacturers are able to distribute the initial costs of precast moulds/set-up over many projects. The recent study by Tam *et al.* (2007b), mentioned above, has shown that construction cost could be reduced by adopting mass production of prefabrication. The issue of standardization when adopting prefabrication is further discussed in the next section.

Prefabrication and building design: standardization and modular design

In the industry survey, the respondents were asked to rate the level of perceived importance and the frequency of use of several design principles when adopting prefabrication in their projects. Overall, the findings revealed that 'repetition of similar precast elements at every floor' was the most important and frequently used design factor when adopting prefabrication (Table 5 and Figure 3). In addition, 'repetition of similar design on more than one block' and 'standard modular design' were also ranked as the next most frequently used design strategy in prefabrication; followed by 'modular design'. As presented in Table 6, in the industry survey, the architects, the engineers and the contractors generally agreed with the above findings. However, it is worth noting that contractors

Table 4 Sampling distribution of the difference of means between conventional construction and precast construction regarding design issues (industry survey): perspectives of architects, contractors and engineers**

Factors	Conventional construction				Precast construction				$\bar{x}_1 - \bar{x}_2$	$\sigma_{\bar{x}_1 - \bar{x}_2}$	t	$t_{Critical}$
	Rank	$\bar{x}_1$	S_{x1}	n_1	Rank	$\bar{x}_2$	S_{x2}	n_2				
Architects' responses												
Quality of end product*	4	−0.35	0.59	17	1	1.18	0.86	17	−1.53	0.25	**−6.05**	−2.021 & 2.021
Opportunity for standardization*	5	−0.53	0.70	17	2	1.00	1.03	17	−1.53	0.30	**−5.07**	
Quality of design	1	0.12	0.68	17	5	0.47	0.92	17	−0.35	0.28	−1.26	
Aesthetic quality*	2	−0.12	0.76	17	3	0.76	0.81	17	−0.88	0.27	**−3.27**	
Ease of maintenance*	3	−0.24	0.55	17	4	0.59	0.69	17	−0.83	0.21	**−3.88**	
Contractors' responses												
Quality of end product*	5	−0.69	0.99	13	2	0.67	1.35	15	−1.36	0.44	−3.06	−2.056 & 2.056
Opportunity for standardization*	2	−0.46	1.22	13	1	0.73	1.48	15	−1.19	0.51	**−2.33**	
Quality of design*	4	−0.62	1.08	13	3	0.67	0.94	15	−1.29	0.39	**−3.35**	
Aesthetic quality*	3	−0.54	1.08	13	4	0.53	1.02	15	−1.07	0.40	**−2.68**	
Ease of maintenance	1	−0.15	1.17	13	5	0.27	1.34	15	−0.42	0.47	−0.89	
Engineers' responses												
Quality of end product*	5	−0.43	0.92	23	2	1.26	0.67	23	−1.69	0.24	−7.12	−2.021 & 2.021
Opportunity for standardization*	1	0.50	0.99	22	1	1.32	0.87	22	−1.82	0.28	**−6.48**	
Quality of design	2	0.22	1.1	23	4	0.74	0.85	23	−0.52	0.29	−1.79	
Aesthetic quality*	4	−0.43	0.97	23	3	1.04	0.81	23	−1.47	0.26	**−5.58**	
Ease of maintenance*	3	−0.09	0.50	23	5	0.57	0.88	23	−0.66	0.21	**−3.13**	

Notes:
* Significant difference between the means for conventional and precast construction.
** Question asked: based on your experience, please comment on the following factors when comparing the use of precast concrete and traditional in-situ construction: 1 = very poor; 3 = neutral; 5 = very good.

Table 5 Sampling distribution of the difference of means between the level of importance and frequency of use of design factors regarding the utilization of prefabrication in buildings**

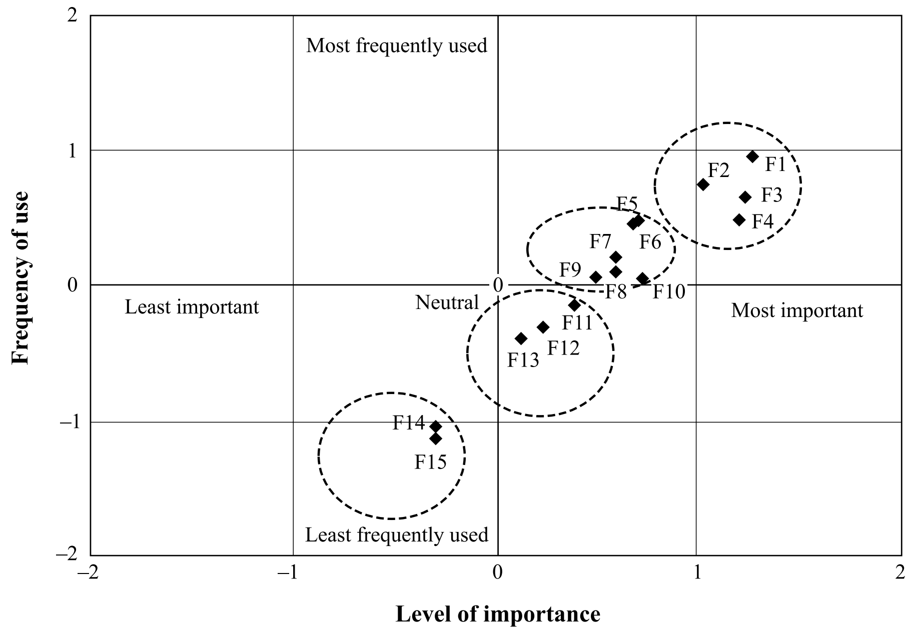
	Factors	Level of importance				Frequency of use/being practised				$\bar{x}_1 - \bar{x}_2$	$\sigma_{\bar{x}_1 - \bar{x}_2}$	t	$t_{Critical}$
		Rank	$\bar{x}_1$	S_{x1}	n_1	Rank	$\bar{x}_2$	S_{x2}	n_2				
Industry survey	Repetition of similar precast elements at every floor*	1	1.26	0.82	80	1	0.96	1.03	76	0.3	0.15	**2.01**	−1.96 & 1.96
	Repetition of similar design on more than one block	4	1.03	1.05	80	2	0.75	1.13	75	0.28	0.18	1.6	
	Standard modular design*	2	1.23	0.91	80	3	0.64	1.08	77	0.59	0.16	**3.69**	
	Modular design*	3	1.2	0.94	80	4	0.49	1.09	77	0.71	0.16	**4.36**	
	Repetition of similar design on more than one site in different location	6	0.69	1.12	80	5	0.47	1.25	75	0.22	0.19	1.15	
	Symmetry of building design	7	0.68	1.19	80	6	0.45	1.1	77	0.23	0.18	1.26	
	Design of building system allowing variations in different blocks*	8	0.59	1.17	78	7	0.21	1.15	76	0.38	0.19	**2.03**	
	Design for ease of construction*	9	0.59	1.45	79	8	0.09	1.43	75	0.5	0.23	**2.15**	
	Design of building system allowing variations in different floors*	10	0.49	1.14	78	9	0.05	1.2	76	0.44	0.19	**2.33**	
	Design of building system allowing various combination of precast elements*	5	0.72	1.07	79	10	0.04	1.22	76	0.68	0.18	**3.68**	
	Design for durability#*	11	0.39	1.45	80	11	−0.14	1.38	76	0.53	0.23	**2.34**	
	Design for ease of maintenance#*	12	0.23	1.36	80	12	−0.31	1.29	77	0.54	0.21	**2.55**	
	Design for adaptability#*	13	0.13	1.35	80	13	−0.39	1.31	77	0.52	0.21	**2.45**	
	Design for dismantling for reuse and recycling#*	14	−0.29	1.35	80	14	−1.04	1.13	77	0.75	0.2	**3.78**	
	Design for recycling#*	15	−0.3	1.44	80	15	−1.13	1.11	77	0.83	0.2	**4.05**	

Notes:
Factors related to sustainable design and construction.
* Significant difference between the means for level of importance and frequency of use of design factors.
** Question asked: based on your experience, please state (1) the level of importance; and (2) the frequency of use/being practised of the following factors when using precast concrete elements: 1 = least important/frequent; 3 = neutral; 5 = very important/frequent.

Table 6 Architects', contractors' and engineers' responses for the level of importance and frequency of use of design factors regarding the utilization of prefabrication in buildings

	Level of importance									Frequency of use/being practised								
	Architects' responses			Contractors' responses			Engineers' responses			Architects' responses			Contractors' responses			Engineers' responses		
	Mean	S	Rank	Mean	S	Rank	Mean	S	Rank	Mean	S	Rank	Mean	S	Rank	Mean	S	Rank
Modular design	1.06	0.97	1	1.47	0.88	2	1.24	0.81	3	0.56	0.96	3	0.73	1.34	5	0.55	0.92	6
Standard modular design	0.72*#	1.04	6	1.53*	0.81	1	1.52#	0.66	2	0.44	1.07	4	1.07	1.12	1	0.75	0.94	2
Symmetry of building design	0.11*#	1.24	15	1.20*	0.91	6	0.86#	0.94	6	–0.06 #	1.03	9	0.73	1.24	6	0.60#	0.86	5
Repetition of similar design on more than one block	0.67*	0.94	7	1.33*	0.87	4	1.19	1.05	4	0.67	0.94	2	0.80	1.28	3	0.74	1.25	3
Repetition of similar design on more than one site in different location	0.28	0.93	13	1.13	1.09	7	0.76	0.81	8	0.28	1.04	7	0.80	1.33	4	0.26	1.29	8
Repetition of similar precast elements at every floor	0.94#	0.85	2	1.33	0.87	3	1.57#	0.66	1	0.67#	0.94	1	0.87	1.15	2	1.53#	0.75	1
Design of building system allowing variations in different blocks	0.78	0.79	4	0.80	1.28	9	0.25	1.22	10	–0.11	0.94	10	0.40	1.45	8	0.05	1.15	9
Design of building system allowing variations in different floors	0.50	0.90	9	0.93∧	1.18	8	0.10∧	1.09	13	–0.28	0.87	12	0.27	1.48	9	–0.11	1.21	12
Design of building system allowing various combination of precast elements	0.44*	0.83	10	1.20*∧	0.83	5	0.20∧	1.17	12	–0.44*	0.90	13	0.53*	1.31	7	0.00	1.34	10
Design for dismantling for reuse and recycling	0.33*	1.15	11	–0.87*	1.15	14	–0.29	1.42	14	–0.83	0.96	14	–1.20	1.17	14	–0.80	1.29	14
Design for recycling	0.33*	1.20	12	–1.00*	1.26	15	–0.38	1.29	15	–0.83	1.07	15	–1.27	1.18	15	–1.15	1.15	15
Design for ease of maintenance	0.89*	0.99	3	–0.53*	1.31	11	0.38	1.43	9	0.17*	1.07	8	–0.80*	1.38	10	–0.40	1.28	13
Design for ease of construction	0.67*	1.00	8	–0.33* ∧	1.66	10	1.10∧	1.23	5	0.44*	1.12	5	–0.80* ∧	1.47	11	0.70∧	1.38	4
Design for adaptability	0.28*	1.15	14	–0.67* ∧	1.40	12	0.24∧	1.15	11	–0.22	1.03	11	–0.80	1.47	12	0.00	1.22	11
Design for durability	0.78*	1.08	5	–0.67* ∧	1.45	13	0.76∧	1.38	7	0.29*	1.18	6	–0.80* ∧	1.47	13	0.35∧	1.31	7

Notes: Architects, n = 18; Contractors, n = 15; Engineers, n = 21.
* Significant difference between the means from architects' and contractors' responses, # between the means from architects' and engineers' responses, ∧ between contractors' and engineers' responses (*t critical*: –2.021 & 2.021); S: standard deviation.



Level of importance and frequency of use	Factors	
Most important and most frequently used	F1	Repetition of similar precast elements at every floor
	F2	Repetition of similar design on more than one block
	F3	Standard modular design
	F4	Modular design
Important and frequently used	F5	Repetition of similar design on more than one site in different location
	F6	Symmetry of building design
	F7	Design for building system allowing variations in different blocks
	F8	Design for ease of construction
	F9	Design of building system allowing variations in different floors
	F10	Design of building system allowing various combination of precast elements
Important and less least frequently used	F11	Design for durability
	F12	Design for ease of maintenance
	F13	Design for adaptability
Least important and least frequently used	F14	Design for dismantling for reuse or recycling
	F15	Design for recycling

Figure 3 Means of level of importance and frequency of use of design factors regarding the utilization of prefabrication in buildings (refer to Table 5 for details)

considered 'symmetry of building design', 'standard modular design' and 'repetition' as more important design factors, which was contrary to the architects' responses. The results presented in Table 5 also reveal that design principles allowing 'variations' were less frequently used when adopting prefabrication in buildings in Hong Kong.

Repetition and standardization

In Hong Kong, the construction of high-rise buildings is prevalent, thus the repetition of prefabricated components at every floor is easily achieved. Symmetry in the block layout and repetition of similar design on more than one block are also commonly adopted to enhance repetition of precast elements, such as in Projects 5, 6 and 7 (Figure 3). In fact, in the private sector, precast concrete components are generally tailor-made for a specific building design. Quantity is, therefore, a major issue when using prefabrication in order to achieve economy of scale and reduce the need for numerous steel moulds. Naturally when more moulds are required, the production process becomes more costly. However, the Building Construction

Authority in Singapore (Building and Construction Authority, 2008) has stated that variations in precast element dimensions using moulds and set-ups could be achieved fairly simply. Generally, precast manufacturers have agreed that a simple change in dimensions, such as height and length, can be accommodated on an existing mould and set-up. Another recent study using a questionnaire survey method (Osmani *et al.*, 2006), has conveyed that prefabricated units, standard dimensions and units, as well as standard materials to avoid cutting, were rarely implemented in building projects. In the industry survey, the respondents indicated that the opportunity for standardization was significantly higher with prefabrication than with conventional construction (t value = –5.07 for architects and –2.3 for contractors) (Table 4). However, standardization across building projects is adopted only in public housing projects in Hong Kong.

Modular design

In public housing projects, the use of prefabrication is generally combined with standard modular design of blocks and elements enhancing prefabricated construction, such as in Project 5. For example, standard precast façade types are associated with standard unit sizes allowing repetitions. According to previous studies using case study analysis of recent completed buildings, the standardization of block designs increases project buildability and speed of construction (Chan and Chan, 2002; Tam *et al.*, 2007b; Building Construction Authority, 2008). The standard block design approach is efficient in providing massive housing supply, even though little consideration is given to site opportunities. Recent public housing developments, such as Project 6 have, therefore, adopted non-standard design layouts with modular precast elements optimizing site opportunities, minimizing constraints, and providing repetitions. Micro-climate studies are also conducted to optimize the positioning and shape of the building blocks.

In the private sector, modular design across projects has been recently introduced and combined with prefabricated building systems, as illustrated in Projects 2 and 3. Although the prefabricated building system developed in Project 2 was fully adopted in Project 3 (with the exception of precast columns and façades), the building designs and layouts in both projects were different. Additionally, the system was not reinvented which allowed builders to save time, as well as construction and design costs. In Project 3, the contractor claimed that with the experience and knowledge gained from Project 2, in terms of the design and production of precast moulds, there was a reduction of total project time by three months.

Design variations

The industry survey results revealed that design principles allowing 'variations' were less frequently used when adopting prefabrication in buildings in Hong Kong. However, in the case studies, Project 2 used a 4m × 4m structural bays modular grid approach which was chosen based on the arrangement of cores and services areas, common space areas, and the flexibility in classroom sizes. In this project, each floor layout is different although the building structure consisted of standard modular precast components such as precast beams, columns and slabs. The different floor layout at every level resulted in greater variety in the design of the façade and dynamism in the pattern of the façade.

Life cycle approach of using prefabrication in buildings

In the industry survey, the respondents were also asked to evaluate the importance and frequency of use of sustainable design principles when adopting prefabrication in their building projects. As shown in Table 5 and Figure 3, 'design for recycling' and 'design for dismantling for reuse and recycling' were considered by the respondents as the least important and least frequently used design strategies with prefabrication. In addition, 'design for adaptability', 'design for ease of maintenance' and 'design for durability' were also ranked as the next set of least important/rarely being practised factors. However, as presented in Table 6, the above factors were seen by the architects as more important when compared with the contractors' responses. Additionally, it is of interest to note that architects ranked the 'design for ease of maintenance' as the third most important factor when using prefabrication (Table 6). In the case studies, one interviewee also commented that 'design for deconstruction is a different kind of knowledge'.

Design for durability and deconstruction

The findings show that design concepts promoting life cycle and waste life cycle are not considered as crucial factors when using prefabrication. It seems that the construction industry in Hong Kong is not yet aiming at achieving closed-loop building materials systems. According to a research by Poon and Jaillon (2002), the average life of a building in Hong Kong is about 40 years, which is comparatively short. By extending the life of a building to 75 years, the amount of construction waste generated due to demolition can be reduced by 50%, and thus demolition waste could be kept away from the waste stream for a longer period. The issue of longevity for new buildings is vital and can be achieved through appropriate design concepts, such as the separation of building layers to avoid conflict between short-term and long-term layers, design for adaptability and flexibility for future needs, design for ease of maintenance, and design for deconstruction. The study by Osmani *et al.* (2006) also pointed out through a questionnaire survey with building professionals that design for deconstruction was rarely implemented in building projects. There are many environmental benefits of deconstruction such as, reductions in waste generation, carbon dioxide, need for new landfill spaces, and new/virgin building materials, thus minimizing the negative impact on the environment (from processing to disposal). In Hong Kong, design for deconstruction (DfD) principles are rarely implemented in prefabricated building projects, although recommended in Building Environmental Assessment Method (2004). The Hong Kong Housing Authority precast components system has demonstrated, to some extent, the application of design for deconstruction in precast staircases. Precast staircase components are generally connected to the landing with a bolted connection, thus allowing dismantling of the precast element and possible reuse in another project.

Design for adaptability

The architects in Project 2 stated that the structural grid (8.4m × 8.4m) was suitable for office use if change of building usage was required in the future. In this project, the possibility for future extension and conversion was considered at the design phase to allow for future needs in facilities and classrooms. According to the architects, flexibility and future extensions were considered in the design in terms of architectural layout (spatial and visual issues), structural design (foundation design allowing additional loading), building services provisions, and statutory requirements (e.g. means of escape, etc.). Although the foundation cost for future extension in the tower and the podium increased by about 10% and 25% respectively, the design provided greater flexibility and was devised to avoid total demolition. However, the architects also indicated that the use of precast concrete elements with in-situ connection would limit the opportunities for dismantling and reusing precast elements at the end of the building's life.

Conclusions

The current industry practices and the views of building professionals in Hong Kong regarding life cycle design aspects of using prefabrication in dense urban environments were examined. The findings have revealed that:

- There is a common view among the respondents that prefabrication contributes to improved quality control (higher quality of end product) and to higher opportunities for standardization. However, in contrast to contractors' and engineers' opinions, the architects felt that the programme time and design time were increased when using prefabrication.
- Prefabrication, combined with modular design and standard precast elements, saves time and construction/design costs, as the prefabricated building system is not reinvented for each project. However, the data gathered in this study have also demonstrated that in some projects, the use of modular design and standard precast components across projects could not be fully implemented due to the narrow site dimensions and typical compactness of sites in Hong Kong's dense urban environments (e.g. in Project 3, precast columns could not be implemented).
- Overall, modular design and standard precast components have been mainly adopted in the public housing projects in Hong Kong. The design of recent public housing developments, such as Project 6, has evolved towards non-standard design layouts with modular precast elements. However, in the private sector, precast concrete components are generally tailor-made for a specific building design. Symmetry in the block layout and repetition of similar design on more than one block are, therefore, commonly adopted to enhance repetitions of precast components.
- Design for recycling and design for dismantling were the least important and least frequently used design strategies with prefabrication, followed by design for adaptability, design for ease of maintenance and design for durability. There is clear evidence that design for deconstruction and adaptability was not yet a priority when adopting prefabrication in Hong Kong. This demonstrates that, so far, the construction industry does not seem to be aiming at closed-loop material principles in buildings.
- The consideration of dry-joints and design for deconstruction early in the building process is indeed needed, so that precast concrete components can be easily dismantled for repair, reuse in another location, or recycling.

Although the findings are specific to the situation in Hong Kong, some concepts may apply to other locations and conditions. Future research should include the study of life cycle assessment and costing approaches when using prefabrication combined with

DfD and IFD building systems. As proposed by Charlson (2008) carbon dioxide generation and material costing aspects in prefabrication should be assessed. Other aspects of the manufacturing process of precast components can also be further investigated in terms of waste generation, production costs, labour requirements and pollution emissions. Additionally, policy measures, such as the effect of higher disposal charges and tax advantages, can be examined to promote life cycle design concepts, such as DfD when adopting prefabrication.

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