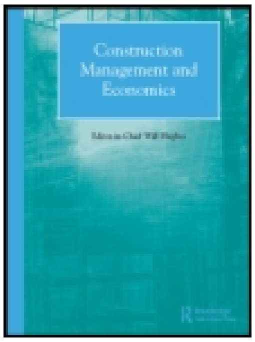

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Demystifying the cost barriers to offsite construction in the UK

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Offsite construction has long been reported as an effective alternative to conventional construction, with wide-ranging benefits. However, a wider take-up has been inhibited by perceived cost barriers which are insufficiently studied. Such cost barriers are addressed, drawing on an examination of the cost performance of four types of construction method: pre-cast concrete cross-wall panel, in-situ reinforced concrete (RC) frame, steel frame and timber frame. Data were collected for 20 medium to high rise residential buildings of eight projects by a leading UK housebuilder over a five-year period (2004–08). In all cases, detailed cost comparisons were completed for build method selection. Cross-wall was found to be consistently cheaper than RC frame or steel frame by 11% to 32% in the projects. The process of developing and innovating cross-wall technology led to sustained cost savings up to 25% from its first use. Cross-wall construction also improved cost effectiveness of 20-storey high rise buildings over other solutions. Cost engineering means for achieving cost reduction and effectiveness are identified, which included efficiency learning, technological innovation, multinational partnering, and 'in-house' build management. The results prove the logic of the experience curve in improving the cost efficiency of offsite construction, and should encourage offsite construction in the future.

Keywords: Cost barrier, cost engineering, offsite construction, pre-cast concrete cross-wall, apartment building.

Introduction

Offsite construction involves the manufacture and pre-assembly of building components, elements or modules before installation into their final locations (Goodier and Gibb, 2007), which represents an innovative alternative to conventional site-based, labour intensive construction. The benefits of offsite construction have been widely studied and include reductions in time, defects, health and safety risks, environmental impact, and whole-life cost with a consequent increase in predictability, productivity, whole-life performance and profitability (see e.g. Gibb and Isack, 2003; Venables *et al.*, 2004; Pan *et al.*, 2007; Tam *et al.*, 2007; Eastman and Sacks, 2008). In the UK, offsite construction has been particularly promoted as an innovative attempt to improve the quality and efficiency of modern developments.

However, the uptake of offsite in the industry remains lower than it could be, with its market value to date estimated up to £6 billion (see Taylor, 2010), equivalent to a less than 6% share in UK construction. Multi-faceted barriers have been found (for a detailed account see e.g. Goodier and Gibb, 2007). A widely reported critical barrier is the higher capital cost, either real or perceived, associated with offsite solutions, which is coupled with a lack of publicly available cost data and information. This case of offsite construction helps illustrate the seeming norm that innovative technology is likely to be associated with higher capital cost than its conventional counterpart, by which its take-up is often inhibited. Nam and Tatum (1988) argued that 'costliness' is a major characteristic of constructed products and contributes to a general tendency in construction in using well-proven methods and materials rather than developing construction technology. Dewick and Miozzo (2002,

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p. 831) concluded that 'in addition to the increased risk and the lack of information and public awareness of new technologies, the costs involved in using a new technology are the single most important barrier'. Lim (2010) also similarly commented that innovation is often classified as a cost-intensive investment in the construction industry with indefinite returns, and that the peculiarities of the industry deem innovation as a poor competitive instrument for direct profits.

The widely held perspective on the higher capital cost of offsite construction technology is therefore addressed in this paper, drawing on an examination of the cost performance of offsite methods in comparison with traditional options. In demystifying the cost barrier, the paper reveals means of achieving cost effectiveness of offsite technology. While acknowledging the need for comparing offsite construction with traditional options on the basis of value (rather than elemental costs) (see Blismas *et al.*, 2006), the paper is focused on investigating the very construction costs which are generally perceived to be higher for offsite compared to traditional construction. The case of medium to high rise residential buildings in the UK is used for the investigation. The analysis covers four types of construction methods, including pre-cast concrete (PCC) cross-wall panel (with or without cladding integrated; in the former case normally referred to as sandwich cross-wall panel) and timber frame systems as examples of offsite construction and steel frame and in-situ reinforced concrete (RC) frame as examples of traditional onsite options.

Offsite construction and pre-cast concrete cross-wall

There are generally four levels of options in the broad spectrum of offsite technologies, i.e. component and subassembly, non-volumetric pre-assembly, volumetric pre-assembly, and modular building (see Goodier and Gibb, 2007). Pre-cast concrete (PCC) cross-wall is a typical type of non-volumetric, pre-assembly, offsite construction and employs factory pre-cast, precision engineered, concrete components, each of which is custom-designed and manufactured off site to suit the specific project (Concrete Centre, 2007). Cross-wall systems incorporate internal walls normally suitable for direct decoration and external walls as either perimeter wall infill or integrating cladding to satisfy functional and aesthetic requirements (Glass, 2000). The walls transfer the floor loads to foundation or transferring podium. Stair and lift cores ensure overall stability, while floors (hollow core, solid concrete or composite construction) act as stiff diaphragms for the transmittal of horizontal forces into shear walls. PCC technology has developed and improved and moved away from its historical problems with design and construction (Glass, 2000), and there is evidence of benefits from using cross-wall (Concrete Centre, 2007). However, the extent of cross-wall applications in the residential sector was observed to be particularly 'rare' (Pan *et al.*, 2008a), which worsened with the sharp decline of apartment buildings following the recent market downturn (Knight Frank, 2009). Although many large housebuilders believed that external and internal walls offer the greatest potential for prefabrication, as reported by Pan *et al.* (2008a), cross-wall is relatively new to UK housebuilding and its adoption is considered costly and risky.

Cost barriers to offsite construction

The cost barrier to offsite construction, although widely reported, is seldom clearly defined but often cited as 'high initial cost' (Goodier and Gibb, 2007), 'increased initial cost' (Nadim and Goulding, 2010), 'higher immediate costs' (Parliamentary Office of Science and Technology, 2003), or 'higher capital cost' (Pan *et al.*, 2007). These generic citations reflect and also contribute to the ambiguity of the concept of the cost barrier.

Real or perceived higher costs of offsite compared to traditional construction have been reported. Lusby-Taylor *et al.* (2004) believed that, although costs of modern methods of construction (MMC) should be less volatile than traditional construction, it was unlikely at the time that costs would be reduced by the use of MMC. Birkbeck and Scoones (2005) identified a general industry perception that housebuilding by offsite methods was more expensive than by traditional construction methods. Pan *et al.* (2007), drawing on a survey of the top 100 housebuilders in the UK, identified the most significant barrier to the use of offsite MMC as higher capital costs, whether perceived or real. Nadim and Goulding (2010) reported that increased initial costs were perceived by 92% of the respondents to their survey as an inhibitor to the wider use of offsite production technology. However, it is important to note the general perception that offsite construction delivers value and reduces the whole-life cost of buildings (see Blismas *et al.*, 2006; Homes and Communities Agency, 2010). Pan *et al.* (2008b) presented evidence showing that the maintenance costs of offsite modules can be almost as low as one-third of in-situ bathrooms. Therefore, this present paper does not attempt to challenge the established claims about value or the whole-life cost of offsite construction, but focuses on addressing the preconception of higher construction costs of offsite.

Real cost data and information on construction are normally difficult to obtain for research. Tan (1999) commented on the complexity of the construction cost relationships and hence the difficulty in getting the data despite the importance of that knowledge. The lack of public cost data and information on offsite construction is even more significant, possibly because of its real or perceived newness, and has been reported as a most critical inhibiting factor to the increased use of offsite construction in the industry (see e.g. Venables *et al.*, 2004; Goodier and Gibb, 2007; Pan *et al.*, 2007). Lusby-Taylor *et al.* (2004) argued from the designers' perspective that limited cost data contribute to the low level of usage of complete modular buildings, volumetric pre-assembly and closed panel systems. The Parliamentary Office of Science and Technology (2003, p. 2) acknowledged that:

> although some house builders argue that MMC is less expensive than traditional methods, industry sources indicate increased costs of around 7–10%. Reasons for the higher costs are difficult to discern because most project financial information is commercially confidential, and traditional masonry building costs vary widely too.

Despite the cost barriers, there is however a paucity of knowledge regarding reducing construction cost but increasing cost effectiveness of offsite construction. This knowledge gap has been verified in a number of industry surveys, e.g. by Pan *et al.* (2007) and Goodier and Gibb (2007), which both advocate better cost data of different offsite systems in comparison with traditional construction and more transparent competitive costing.

The cost barriers to offsite construction reviewed above can be summarized as comprising four aspects: (1) the ambiguity of the concept of cost barrier; (2) consequently real or perceived higher cost of offsite solutions compared to traditional options; (3) a lack of cost data and information on offsite construction; and (4) a paucity of knowledge on reducing construction cost but increasing cost effectiveness of offsite. A consequence of the cost barriers is that builders and developers are reluctant to adopt offsite construction methods (Pan *et al.*, 2008a), albeit their widely reported non-cost, or life cycle cost, benefits and value. Previous studies (e.g. Pasquire and Gibb, 2002; Blismas *et al.*, 2006; Chen *et al.*, 2010) have advocated value-based performance measurement, by which to attempt to shape the industry's technology decision thinking. The efforts are worthwhile, but their effectiveness is somewhat impaired, pragmatically reflected in the still low level of take-up of offsite production. Also, as revealed by Ball (2010), builders and developers are becoming more concerned about the significantly rising build costs of achieving increasingly stringent building standards. The perception of the high construction cost of using offsite construction methods, albeit ambiguous, seems deeply embedded in the mentality and practice of builders, developers and their professional advisers. Similar to some other innovative technology, offsite construction falls into a trap, entangled with the myth of 'cost intensive investment' and 'high capital cost'. It is therefore imperative to address the cost barriers in order to help achieve a step-change towards a faster offsite take-up.

Within such theoretical and practical contexts, this paper examines the construction cost performance of offsite in comparison with conventional options, and reveals how the cost profile of offsite construction evolves with time, experience and learning of the adopter, and management of the technology. The questions guiding the research were:

- Does the use of offsite construction methods necessarily involve higher construction cost than conventional options?
- Can such cost of offsite construction be reduced over time and experience?
- How can any construction cost saving of building by offsite methods be practically achievable?

Research method

Research design

The research on which this paper reports was designed using the principles of case study, providing an in-depth, analytical and chronological account of unit of analysis (Yin, 2003). The 'unit of analysis' in this research is interpreted as the construction cost performance of offsite methods, which was analysed in comparison with traditional building methods, as well as over a period of time so the evolution of the cost profile of offsite construction could be explored. With such a design, the study was carried out with a UK leading housebuilding company. This company was a prominent industry player, building around 2500 new homes per annum at the time of this study. The company was proactive in its adoption of innovative and modern methods of construction, and aspired to improve business efficiency by standardizing design processes through the investigation into, and learning from, the use of offsite construction methods. More importantly, the company had completed a number of building projects that involved offsite methods during the period from the late 1990s/early 2000s when offsite and modern methods were promoted by the UK government (e.g. via the Egan Report (Egan, 1998) and the Sustainable Communities Plan (Office of the Deputy Prime Minister, 2003)) to the date of this research, which coincided with the recent economic downturn. These features provided a context in which the cost of offsite could be examined both comparatively (i.e. evaluated against traditional options) and chronologically (i.e. a study of its evolution). The use of such a company for the research, albeit selective, addresses the research design.

Nevertheless, the success of implementing the research design would not be possible without guaranteed access to reliable and valid cost data and information. Such access was however enabled by the 'convenience' derived from the collaborative research relationship between the researcher and the company, which was built through previous research and professional collaboration. The collaboration also encouraged the co-production of new knowledge between the researcher and practitioners (see Green *et al.*, 2010).

Generalizability is understood in terms of Hammersley's (1998) 'theoretical inference', whereby conclusions move from the specific to the wider conceptual level, drawing on extant theory and previous research findings. Such generalization should follow a replication rather than sampling logic (Yin, 2003). Therefore, while it is useful to reveal how much more or less is the cost of offsite construction compared to the cost of traditional methods, it is more important to examine how the cost of offsite construction evolves over time and with experience, and how cost savings and effectiveness can be achieved. Nevertheless, such understanding that hopefully is contributed via this study should benefit from further investigation in a wider context (e.g. with other building companies who have similarly explored offsite construction). However, the paucity of studies investigating offsite construction costs suggests that this present research has the potential to make an important contribution to the ongoing debate.

Case studies more often take a qualitative perspective, concerned with exploring, describing and explaining a phenomenon, while they sometimes make substantial use of quantitative research methods (Bryman, 1989). The benefits of such a combined approach include a strong grounding in reality, as well as utility to practitioners and decision-makers with supporting evidence. This approach is taken in this study to guide the quantitative analysis of cost and the implications of cost evolution and engineering. Three research and analysis strategies were employed: (1) compare cost between offsite construction solutions and conventional options; (2) investigate the cost evolution of offsite construction; and (3) identify cost engineering means for reducing construction cost and increasing cost effectiveness. Given the focus of this research on construction cost, non-cost items (e.g. construction programme, sustainability issues and health and safety) that may have cost implications, unless embedded in cost terms (e.g. preliminaries), are not considered in the analysis presented in this paper.

The projects and construction methods studied

The study included a series of eight residential development projects which were carried out or planned by the housebuilder during a period of five years from 2004 to 2008. These eight projects, labelled from A to H (Table 1), were located in North West England, and included 20 medium to high rise buildings (ranging from six to 20 storeys), providing 1922 units of apartments in total (Table 1). All the buildings under Projects A to F were constructed, while Projects G and H were at final cost plan stage but their construction was suspended because of the economic downturn at the time of this study.

Pre-cast concrete (PCC) cross-wall systems were used for the residential part of all the buildings (with cladding integrated into sandwich cross-wall panels for Projects G and H, Table 1). A timber frame method was estimated for Project B as an offsite alternative to cross-wall. In-situ reinforced concrete (RC) frame and steel frame methods were estimated for Projects A, D and F and Projects A and D, respectively, as two conventional construction alternatives.

Data collection and analysis

The data collection and analysis were supported by the collaborative relationship between the researcher and the company. A senior member of the estimating department of the firm acted as the conduit for communication. A number of key steps were taken for the data collection and analysis, although such processes often involved close and, sometimes, iterative communications (via e-mail, phone calls and face-to-face meetings) with the main contact at the company. First, the details of the eight projects and the four types of construction methods were obtained and verified. The details included: time of construction, numbers of buildings, storeys and apartments, site specifics, design specification, procurement, and construction method and building detail, which are summarized in Table 1.

After that, a template of cost data collection (in the form of a spreadsheet) designed by the researcher was provided to the company for verification. The refined spreadsheet was then used for the company to fill in,

Table 1 Details of projects and construction methods

Project	A	B	C	D	E	F	G	H
Year of construction	2004	2005	2006	2007	2007	2008	2008[a]	2008[a]
No. of buildings	2	1	3	2	3	1	5	3
No. of storeys	9/7	5	13/8/5	10/9	7/5/4	9	16	20
No. of apartments	47/55	80	72/57/42	68/47	119/77/64	152	605	437
Net residential (sqft)	61 200	44 880	97 812	75 005	138 060	*77 520*	*316 889*	*217 074*
Sqft/apartment	600	561	572	652	531	510	524	506
Commercial area	0	0	0	0	0	19 000	39 000	10 000
Car park solution	Surface	Surface	Undercroft/surface	Surface	Undercroft/surface	Undercroft	Undercroft/basement	Undercroft/surface
Procurement	Contractor 1; newly formed project team	Contractor 1	Contractor 2; extended supply chains; developed effective project team	Contractor 3; built supply chain database; R&D benchmarking	Contractor 2	Contractor 2 with partnering agreements	Contractor 2; multinational supply chains	As Project G
Construction method	Pre-cast concrete (PCC) cross-wall system: cross-wall panels (150mm) and PCC concrete floors	As Project A	As Project A, and in-situ concrete for off-grid undercroft car park	As Project A, with PCC curved façade	As Project A, but 125mm wall panels; PCC undercroft design to avoid in-situ concrete	As Project A, and in-situ concrete podium	PCC cross-wall system, with sandwich external wall panels, no on-site cladding or external scaffold	As Project G, with additional engineering work to ensure structural stability at 20 storeys
Building detail	Full external scaffolding, no basement	As Project A	Mast climbers (no external scaffolding), on- and off-grid undercroft car park	No basement, curved façade	On- and off-grid undercroft	3-storey podium	Cross-wall with sandwich panels, with podium	As Project G

Note: [a] Planned, designed and estimated for, while construction was suspended owing to the economic downturn.

drawing on their internal project cost database. The cost data were focused on the construction cost of the projects, with a full breakdown including preliminaries, substructure, superstructure, external works/services and contractor overheads. The cross-wall construction costs were actual final accounts, except for those in Projects G and H where a combination of actual cross-wall quotations and estimated fit-out costs were used. The other construction methods were evaluated using actual quotation values from the supply chain of the company recorded in their project cost database.

The data collected were then initially analysed, revealing the comparative case of pre-cast concrete cross-wall to the other methods and the evolutionary case of cross-wall. The building designs and dwelling types of the eight projects were consistent, and implications of the organization and project management context on skewing cost analysis were minimized. However, the projects were different from each other in terms of the following variables:

(a) Project and site specifics, and therefore different planning, development, sales and marketing.
(b) Time of construction and completion.
(c) Whether or not including commercial areas.
(d) Car parking solutions, e.g. surface (i.e. car parking provided outside the perimeter of the building with apartments at ground floor level), undercroft (i.e. car parking provided at ground floor level under the apartment block thus requiring some form of transfer structure at upper ground floor level, or continuation of load bearing walls through to the ground at car park level), basement or any combination.
(e) Amount of residential floor areas.
(f) Number of apartments/plots.

Therefore, a number of quality control techniques (against the variables above) were used to convert the cost data to that on a common base for effective comparison and analysis:

(a) The paper is focused on construction cost. Land, planning, development, and sales and marketing costs were not included.
(b) All costs were indexed to the third quarter of 2008 using the Building Cost Information Service (2010) All-in Tender Price Index.
(c) Costs of any non-residential areas (e.g. lower floors of undercroft/basement car park and commercial areas) were excluded from the analysis, as they only applied to some of the projects and adopted specific design specifications, and therefore would skew analysis.
(d) Covered in (c).
(e) A combination of the measures '£/sqft (net residential habitable area)', '£/plot' and '% of total construction costs' were used to normalize cost comparison.
(f) Covered in (e).

Furthermore, the results of the initial analysis (after the quality control 'treatment' as explained above) and the data stored in the spreadsheet were verified by the senior member of the estimating department of the company. The verification also involved assessing the relevant company and project documents. The analysis and the results were discussed with the other key personnel of the company for the use of offsite methods, which covered technical, construction and procurement matters. These discussions took place in the form of individual interviews and a group discussion facilitated by the main contact at the company for this study. The verified data were used for final analysis on which this paper reports.

Results and analysis

Defining and justifying cost items

The analyses are focused on construction costs, which include preliminaries, substructure, superstructure, external works/services, and contractor overheads (Table 2). Superstructure is further broken down to structure, external envelope, internal party walls, balcony structures, internal fit-out, and mechanical and electrical (M&E) (Table 2). The overarching purpose of focusing on these cost items is to provide an effective 'like-for-like' comparison in addressing the research questions.

Cost comparison

Four cases of cost comparison are included in the analysis:

- Project A: PCC cross-wall vs. RC frame vs. steel frame
- Project B: PCC cross-wall vs. timber frame
- Project D: PCC cross-wall vs. RC frame vs. steel frame
- Project F: PCC cross-wall vs. RC frame

Total construction costs

The total construction costs (TCC) in £/sqft of PCC cross-wall systems were considerably lower than RC frame in Projects A (by 13%), D (by 20%) and F (by 14%), and greater savings were shown when com-

Table 2 Defining cost items and analyses

No.	Cost item	Definition/explanation	Cost comparison	Cost evolution	Cost engineering
1	Preliminaries	All preliminary costs	✓	✓	
2	Substructure	All costs associated with substructure			
3	Superstructure	Residential areas only, excluding undercroft/basement and commercial areas	✓	✓	✓
3.1	Structure	Superstructure cost, key item to compare cross-wall and others	✓	✓	✓
3.2	External envelope	Same as above	✓	✓	✓
3.3	Internal party walls	Same as above	✓	✓	✓
3.4	Balcony structures	Same as above	✓	✓	✓
3.5	Internal fit-out	Same as above	✓	✓	
3.6	M&E costs	Same as above	✓	✓	
4	External works/services	Project and site specific			
5	Contractor overheads	Typically 8% of construction costs (items 1 to 4) for schemes using a main contractor procurement route	✓		
All	Total construction costs (TCC)	Include items 1 to 5, but exclude land, planning and design, sales and marketing, maintenance, and developer's overheads.	✓	✓	✓

pared to steel frame solutions in Projects A (by 11%) and D (by 32%) (Figure 1). Given the maximum nine storeys of the buildings in these three projects, timber frame was considered technically not viable owing to the risk of progressive collapse.

For Project B (maximum six storeys), timber frame was considered technically feasible and was estimated for, which showed that its associated construction cost would be marginally lower (by 3.5%) than the cross-wall solution (Figure 1). However, cross-wall was still utilized, because it was considered more technically robust (less shrinkage and fire proofing for M&E), easier to finish, less fit-out (insulation/plaster-boarding for party walls) and therefore marginally faster, than timber frame. Also, a timber frame floating floor was estimated more expensive than screeds to cross-wall floors.

Preliminary costs

The preliminary costs (£/sqft) of building using cross-wall were lower than any of those of the other construction methods in Projects A (by 17%), B (by 9%), D (by 21%) and F (by 39%). This result is supported by the measurement of preliminary costs as percentage of TCC, which shows a lower share of cross-wall construction in Projects A (8.8%), B (8.9%), D (8.9%) and F (7.2%) than other construction solutions (over 9% or 10%) except the case of steel frame in Project D (7.8%) which was due to the significantly higher superstructure costs of steel frame construction.

All preliminary cost savings were of pure preliminary items, as a result of time-related cost savings for items such as site management, distribution (cranes, forklift trucks, hoisting, etc.), accommodation (hire of site offices and facilities), plant items and site security. Typically the weekly site running cost for schemes of the size studied was found to be around £12k. The interviews explicated that cross-wall construction is faster, with anticipated completion in 15% less time than RC frame or steel frame construction. Also, a cross-wall system is simpler and requires less management. Therefore, considerable cost savings were realized for the fast PCC cross-wall solution. These features also led to a faster pace improving return on capital employed.

Superstructure costs

The superstructure costs (£/sqft) of PCC cross-wall systems were generally lower than those of RC frame in Projects A (by 5%), D (by 14%) and F (by 3%), and also cheaper than steel frame solutions in Projects A (by 2%) and D (by 30%).

The analysis of superstructure cost breakdowns suggests that the cost difference between these

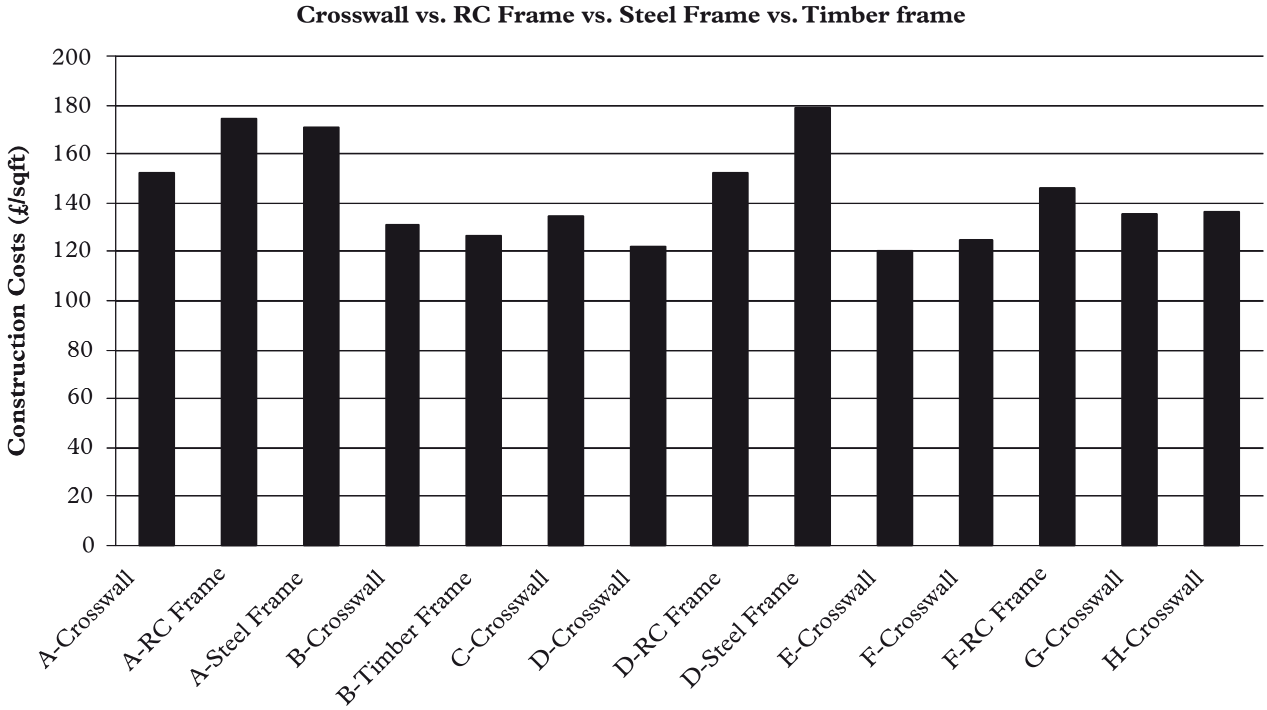

Figure 1 Total construction cost comparison

construction solutions was largely attributed to their technical features and consequent implications for construction and management. These features included that external walls were part of cross-wall systems, while RC and steel frame solutions would require infill walls (in Projects A, D and F); that cross-wall systems included load-bearing internal walls, while RC and steel frame would require stud or blockwork party walls (in Projects A, D and F); that the design of Project D was more complex (with two drum-shaped towers) for which the cross-wall price was kept to levels similar to that in previous projects, while RC frame was quoted more expensive as a result of the curved elevations and infill to external walls; and that steel price was much higher than the price of concrete or timber, as a result of the then volatile steel market (in Projects A and D).

In Project B, timber frame construction would require marginally lower (by 6%) superstructure costs than PCC cross-wall. However, the company preferred the fast-speed construction and time-related cost savings of cross-wall.

Contractor overheads

Contractor overheads were considered by the company as 8% of direct total construction costs (i.e. including preliminaries, substructure, superstructure and external works). This 8% was perceived to be typical for a main contractor procurement route at the time of the cost analysis. However, contractor overheads only applied to the RC frame and steel frame options, but not to cross-wall or timber frame construction because the housebuilder was willing to build using the perceived simpler cross-wall system in-house and was experienced and competent with timber frame construction. For RC or steel frame, they would need to engage a main contractor and pay the main contractor 8% overheads. Indeed, all RC and steel framed schemes in the company in the past have been built with a main contractor engaged.

Cross-comparative analysis

Amalgamating the comparative analysis of preliminaries, superstructure and contractor overheads (measured as % of TCC) above suggests two interesting patterns. One is that TCC were more sensitive to superstructure costs than to preliminaries or contractor overheads. The other is that the use of PCC cross-wall made more significant impacts (cost reduction as % of TCC but not necessarily as a net cost reduction) on preliminary costs and contractor overheads than on superstructure costs. These observations help explain the result that superstructure costs of PCC construction (measured as % of TCC) were higher than any of the other construction solutions in all the four projects (A, B, D and F).

Cost evolution

The costs of PCC cross-wall in the eight projects were compared with each other, to illustrate the cost evolution of such construction solution.

Total construction costs

The evolution of total construction costs (TCC) of cross-wall was first analysed with external work/services excluded (for perceived irrelevance). TCC were the highest in Project A (£140.15/sqft), dropped significantly in Project B (by 14% to £120.50/sqft), continued decreasing in Projects C and D, reaching the trough in Project E (£105.28/sqft) (Figure 2). The overall cost reduction during the five projects (A–E which were implemented in a chronological order) was 25%. The costs climbed up in Project F (£114.551/sqft) and remained around £120/sqft in Projects G and H (Figure 2). The company explained that the cost increase in Projects F–H was due to the increasing building complication of the schemes, which was reflected in the inclusion of undercroft/basement car parks and lower-level commercial areas and the 'unusual' building height of 20 storeys rather than the typical nine storeys in the previous projects. Nevertheless, there was still a 14% cost reduction in the later schemes compared to the first use of PCC cross-wall system in Project A.

TCC (measured in £/sqft) were also analysed with external work/services included; this analysis indicates a similar pattern of cost evolution in the eight projects (Figure 2). The overall cost reduction during the first five projects (A–E) declined but was still significant (21%), and the typical cost savings compared to Project A were around 11%.

TCC evolution was also revealed using measurements in £/plot. Similarly, TCC with external work/services excluded were again the highest in Project A (£84 090/plot), dropped significantly in Project B (by 20% to £67 598/plot), reaching the trough in Project E (£55 903/plot) (Figure 3). The overall cost reduction during the five projects (A–E) was 34%. The costs climbed up in Project F (£58 400/plot), Project G (£63 572/plot) and Project H (£60 290/plot), with still over 20% cost reduction compared to Project A (Figure 3).

TCC evolution (with external work/services included) indicates a similar pattern (Figure 3). The overall cost reduction during the first six projects (A–F) declined but was still significant (30%), and the typical cost savings of the projects compared to Project A were around 20%.

The cross-analysis of TCC measured in £/sqft (Figure 2) and £/plot (Figure 3) shows similar decreasing patterns of cost evolution of PCC construction in the projects over the years. However, the decreasing trend of TCC measured in £/plot is steeper and more thorough than measured in £/sqft. Such difference was affected by the dwelling unit size, and the two measurements are convertible by multiplying with a conversion coefficient of sqft/plot. The dwelling unit size of the eight projects, averaged 557 sqft/plot, shows a decreasing trend (from A to H), while the units of Project D (652 sqft/plot) were significantly larger than any of the

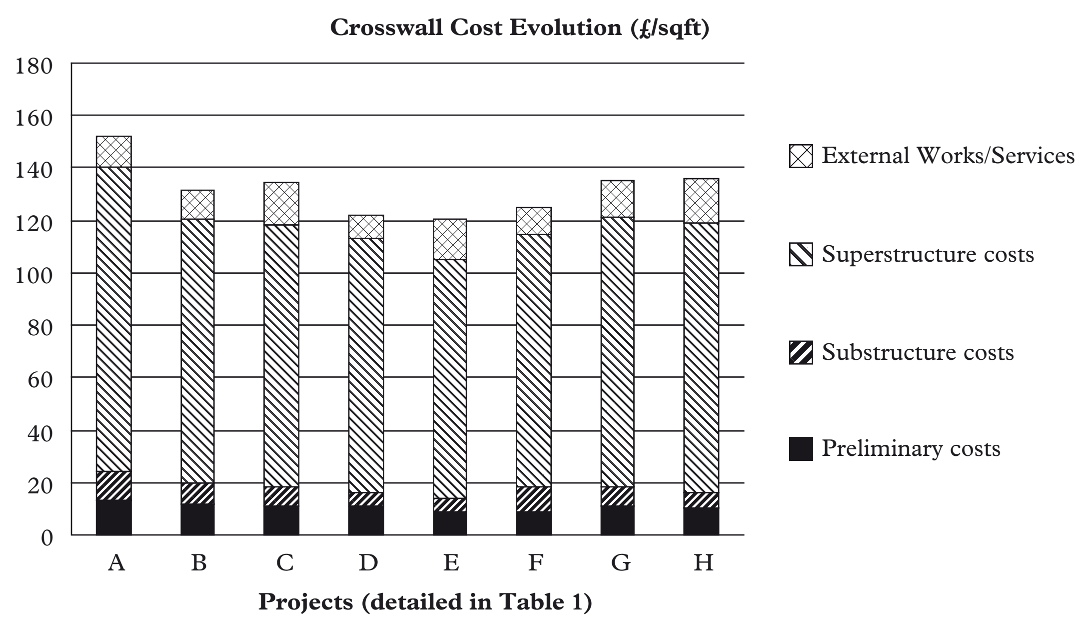

Figure 2 Cross-wall cost evolution (TCC measured in £/sqft)

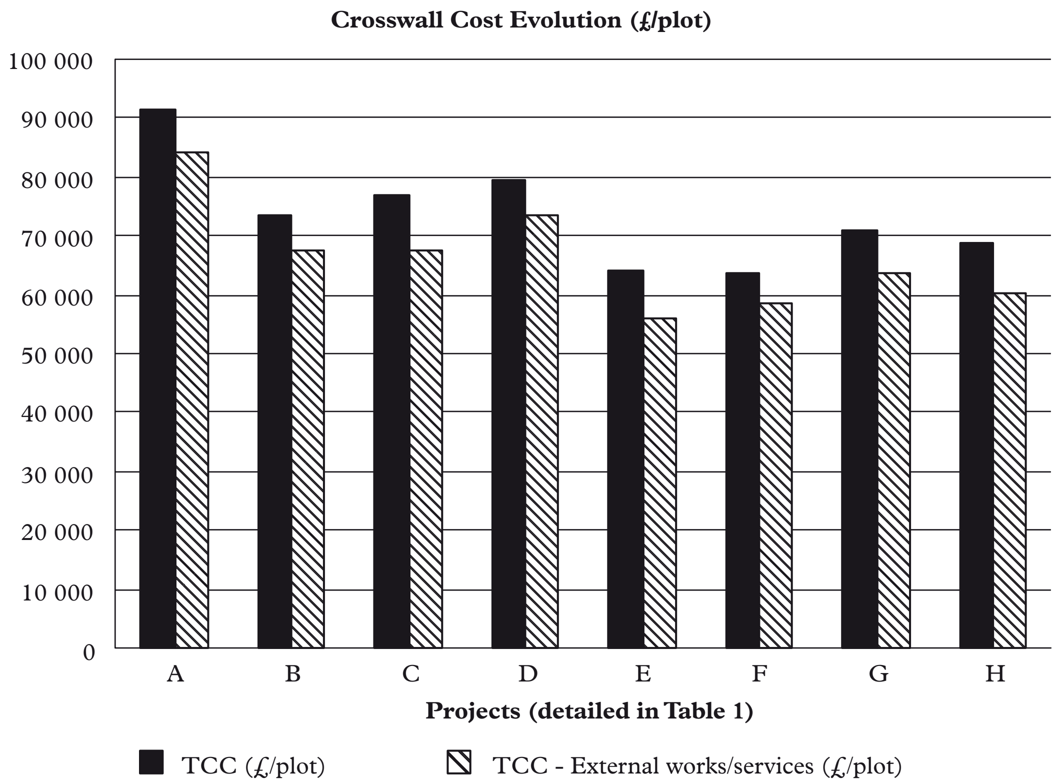

Figure 3 Cross-wall cost evolution (TCC measured in £/plot)

rest. This sharper trend of TCC measured by £/plot also reflects the company's then business strategy, i.e. delivering smaller flats to the then urban residential market.

Preliminary costs

Preliminary costs decreased over the first five projects, with the highest £13.40/sqft in Project A and the lowest £8.64/sqft in Project E (presenting a 36% reduction), climbing to £9.05/sqft in Project F, and stabilizing around £11/sqft in Projects G and H (Figure 2). After the initial use, the company became familiar with the cross-wall system. A consequence of that was more predictable and realized time-related cost savings in later schemes. The climb of preliminary costs in the more recent three projects, particularly Project G, was due to the increased complexity of building for undercroft/basement car parks, commercial areas and higher storeys. The company commented that the overall preliminary cost reduction was enabled by the shortened onsite construction period and reduced number of site staff per 100 plots (but without compromising site management quality) using offsite produced cross-wall panels.

Preliminary costs were also analysed as % of TCC, which averaged 8.2%, with the highest 8.9% in Projects A, B and D and the lowest 7.2% in Projects E and F. The evolution of preliminary costs over Projects A–F indicates a decreasing share of TCC (Figure 4). This result suggests a faster decreasing trend of preliminary costs of PCC construction than of TCC in Projects A to F. The share of preliminary costs increased in Projects G (8.3%) and H (7.7%), which was considered a result of building to 20 storeys rather than the typical nine storeys and the complexity of interfaces between offsite construction and in-situ concrete for lower-level commercial areas.

Superstructure costs

Superstructure costs of cross-wall construction were the highest in Project A (£116.19/sqft) and the lowest in Project E (£91.57/sqft), indicating a maximum 21% reduction of such costs from the first cross-wall project (Figure 5). Superstructure costs of the projects except A were reasonably stable (m = £98.58/sqft, SD = 4.17), while a more important observation is that the costs continued dropping from Project A to E, rose in Project F (£95.86/sqft) and stabilized in Projects G and H (around £103/sqft) (Figure 5). The rise of superstructure costs in the three later schemes (particularly G) was considered to result from the rapidly increasing number of storeys of the buildings

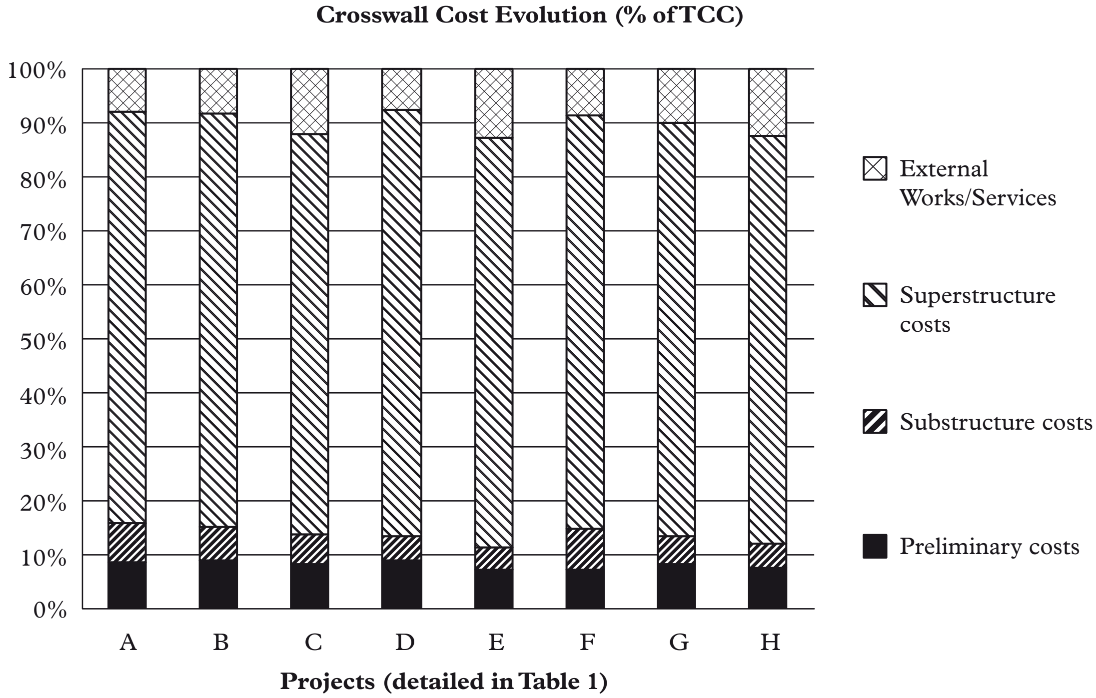

Figure 4 Cross-wall cost evolution (cost items as % of TCC)

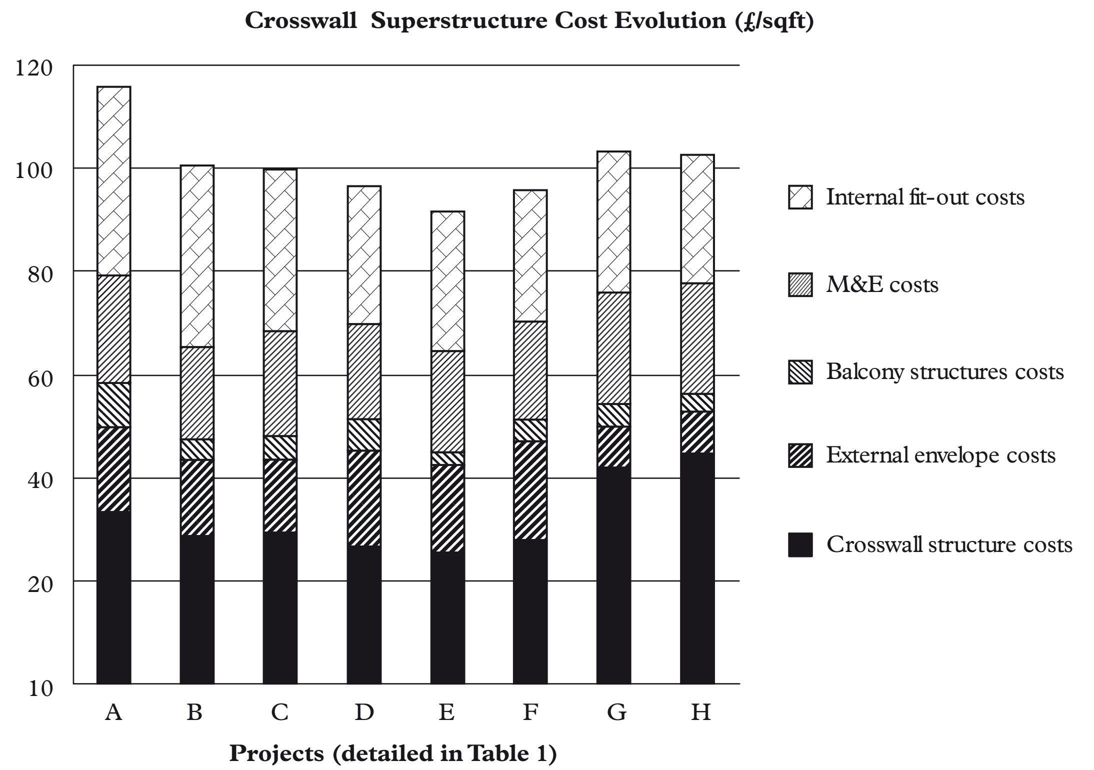

Figure 5 Cross-wall superstructure cost evolution (measured in £/sqft)

(up to 20 storeys) and complexity of interface with lower-floor construction. It was also due to a strategic technological development change to sandwich concrete panels with external cladding integrated which was partially offset by reduced external envelope costs.

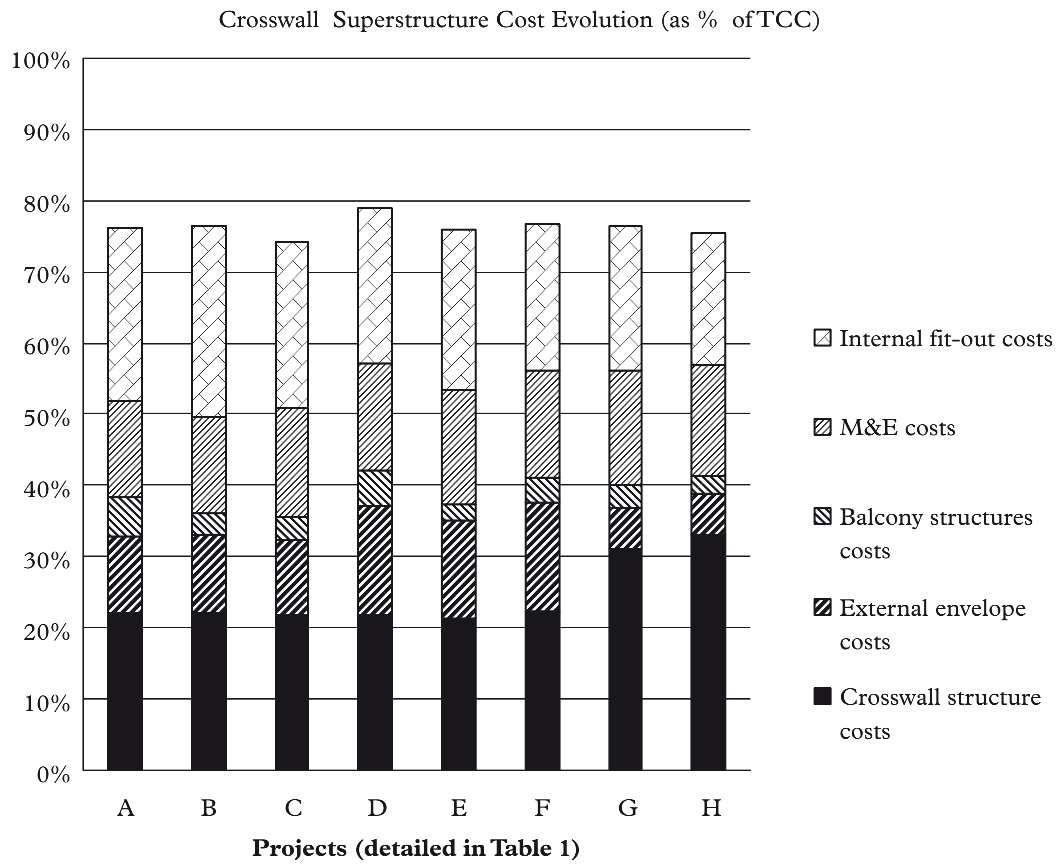

Figure 6 Cross-wall superstructure cost evolution (measured in % of TCC)

Superstructure costs, measured as % of TCC, stabilized across all the eight projects (Figure 4 and 6), averaging 76.3% with a SD of 1.3%. This result, coupled with the observed evolution patterns of superstructure costs (Figure 5) and TCC (measured in £/sqft) (Figure 2), suggests a virtual synchronization of changes of these costs. Such suggestion is further tested below using correlation analysis.

Superstructure cost breakdowns

The superstructure cost breakdowns (Table 2) were analysed using measurements in £/sqft (Figure 5) and % of TCC (Figure 6). The most important observation is the dramatic increase of structure costs (coupled with a sharp decrease of external envelope costs) in Projects G and H compared to the others. This reflects the construction technology development for external walls from typical loadbearing cross-wall panels to sandwich panels (with cladding integrated into the panels). The costs of the balcony, M&E and internal fit-out were dependent on the design specifics of the projects. The evolution of these three cost items correlated with the overall superstructure costs, and no particularly noticeable evolution pattern is observed.

Correlation analysis of cost evolutions

Bivariate analysis was carried out to reveal any correlations between the evolutions of the cost items. The analysis in £/sqft shows strong correlations between TCC and superstructure ($r = 0.975$, $p = 0.000$) and preliminaries ($r = 0.833$, $p = 0.01$, 2-tailed), and between preliminaries and superstructure ($r = 0.878$, $p = 0.004$), balcony ($r = 0.773$, $p = 0.025$) and fit-out ($r = 0.791$, $p = 0.019$), and between superstructure and balcony ($r = 0.764$, $p = 0.027$), and between structure and envelope ($r = -0.902$, $p = 0.002$) and M&E ($r = 0.787$, $p = 0.020$) (Table 3). These results suggest that the changes to TCC of projects by cross-wall methods were mainly attributable to the changes to superstructure costs and then to preliminaries, but not really to substructure or external works. The changes to superstructure costs were more attributable to the changes to the sum of structure and envelope costs, and to balcony costs, rather than to fit-out or M&E costs. These results reflect well the nature of cross-wall construction, i.e. using loadbearing pre-cast concrete external and party walls which eliminate the requirement for external infill walls (which are associated with

Table 3 Correlation *r(p)* analysis of cross-wall cost evolutions (£/sqft)

	Preliminaries	Substructure	Superstructure	Structure	Envelope	Balcony	M&E	Fit-out	External works	TCC
Preliminaries	1	0.495	0.878	0.251	−0.153	0.773*	0.249	0.791	−0.136	0.833
		(0.213)	(0.004)	(0.548)	(0.717)	(0.025)	(0.552)	(0.019)	(0.749)	(0.010)
Substructure		1	0.636	−0.040	0.271	0.560	0.011	0.604	−0.361	0.618
			(0.090)	(0.925)	(0.516)	(0.149)	(0.979)	(0.113)	(0.379)	(0.103)
Superstructure			1	0.470	−0.246	0.764*	0.522	0.648	0.023	0.975**
				(0.239)	(0.557)	(0.027)	(0.185)	(0.082)	(0.956)	(0.000)
Structure				1	−0.902**	−0.027	0.787*	−0.186	0.490	0.506
					(0.002)	(0.949)	(0.020)	(0.659)	(0.218)	(0.201)
Envelope					1	0.299	−0.699	0.163	−0.635	−0.327
						(0.472)	(0.504)	(0.700)	(0.091)	(0.429)
Balcony						1	0.149	0.551	−0.423	0.649
							(0.725)	(0.157)	(0.296)	(0.082)
M&E							1	−0.093	0.697	0.611
								(0.827)	(0.055)	(0.108)
Fit-out								1	−0.169	0.649
									(0.688)	(0.082)
External works									1	0.211
										(0.615)
TCC										1

Notes: ** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

conventional RC frame construction) and significantly reduce the building envelope work.

The analysis in% of TCC indicates that structure costs and external envelope costs were strongly negatively correlated ($r = -0.854$, $p = 0.007$, 2-tailed). There were also strong correlations identified between external work/services and superstructure costs ($r = -0.730$) and balcony ($r = -0.718$) at the $p < 0.05$ level (2-tailed), and between M&E and fit-out ($r = -0.752$, $P < 0.05$, 2-tailed). No other correlation was observed at the $p < 0.05$ level (2-tailed). These results in percentage of TCC verify the previous analysis using £/sqft.

Cost engineering

Through the process of the eight projects, the company trialled the initial cross-wall method, modified the approach and adapted it to the business context and project specifics (and also adapted its management and procurement in order to optimize the use of cross-wall technology). The achievement of continuous cost reduction and effectiveness was attributed to the application of a number of cost engineering means by the company working with its supply chain. These cost engineering means were interrelated with innovation in the design, technology and procurement management of cross-wall systems.

Means 1: Efficiency learning (continuous)

Through the five-year process the company advocated efficiency learning from adopting and utilizing PCC cross-wall technology. For instance, although Projects A and B were similar, e.g. with full scaffolding, no basement, supplied and built by the same specialist contractor, 14% TCC savings were achieved. This was largely attributed to the efficiency learning and consequently reduced preliminaries and superstructure costs. The solution became proportionally cheaper as the developer and its subcontractors became familiar with the system.

Means 2: Technological innovation (continuous)

This means was reflected in the overall process of delivering the projects.

- *Means 2.1: Replacing full external scaffolding by mast climbers (Project C onwards)*

  This means enabled the reduction of preliminary and superstructure (envelope) costs, particularly for much taller buildings. The company commented that savings of £5/sqft against estimate were made from the use of mast climbers instead of scaffolding. Also, the means helped improve construction speed and reduce H&S hazards on site.

- *Means 2.2: Developing 125mm cross-wall panels from usual 150mm (Project E)*

  This practice was adopted to reduce structure costs, without compromising the structural quality of the building. Nevertheless, the 125mm panels proved to impair the acoustic performance of the party walls, for which an extra layer of plasterboard was applied to each side of the party walls. Such extra work offset part of the structure cost savings, and was considered inefficient. The cross-wall panels were changed to 150mm in the following projects.

- *Means 2.3: Re-engineering design to enable on- or off-grid cross-wall undercroft/podium structures to avoid in-situ concrete work (Projects C and E onwards)*

  This practice had little impact on the costs of the residential part of the buildings. However, it simplified the interfaces between undercroft/ basement car parks or lower-level commercial areas and superstructure for residential, and therefore reduced the overall project costs. It improved the cost viability of the schemes as a whole.

- *Means 2.4: Developing sandwich cross-wall panels (Projects G and H)*

  The PCC panel system was developed to include sandwich external panels and estimated for Projects G and H. This new development eliminated onsite cladding and external scaffolding which would be required for RC frame and steel frame solutions. The sandwich panel system was novel to UK residential building at the time, and was considered to be a more appropriate construction solution to achieving better value for high rise buildings.

Means 3: 'In-house' build management (continuous)

The company adopted in-house build management for all the projects, i.e. without engaging a main contractor. This practice eliminated contractor overheads in cross-wall schemes, which were associated with RC frame and steel frame construction. It also provided the company with a good opportunity to develop in-house design and build skills and capability.

Means 4: National and international partnering (Project F onwards)

The company worked with three suppliers and specialist contractors for Projects A to E, and formed a partnering relationship with one of them from Project F onwards. The company modified the design, engineering and contractual arrangements to suit partnering. This means enabled the company to continue achieving the cost reduction and effectiveness of cross-wall construction, and also to develop the novel sandwich PCC panel system for building high rise up to 20 storeys (Projects G and H) in collaboration with the manufacturers and suppliers in Belgium. The new system required the company to manage its multinational supply chains to deliver cross-team solutions for the interfaces between trades and components. The established partnership enabled a reduction in the potential for contractual disputes between the developer and the main contractor compared to the case using traditional build methods.

The application of the means helped reduce construction cost and improve cost effectiveness, which sustained the use of cross-wall technology in the projects; the good practice enabled realization of better value from the journey of innovation, and improving technical and managerial performance of the organization.

Discussion

The results of the cost comparison, evolution and engineering are further evaluated drawing on existing knowledge.

Cost comparison: offsite vs. traditional methods

The cost comparison results challenge the general perception of higher construction costs of offsite construction compared to conventional options. The results add to the few research/industry attempts to address the cost barrier to offsite construction. A key example is the Design for Manufacturing (DfM) Competition (Communities and Local Government, 2006; Homes and Communities Agency, 2010) which aimed to build quality homes with a construction cost of £60 000 (at 2005 prices). Such construction cost covered preliminaries, foundation, superstructure, services, overheads and fees, but not land and sales or marketing, which provides a relatively common base for comparison with the results from the present study. Both studies demonstrate a generally consistent achievement of the construction costs per dwelling below £60k, which adds evidence demonstrating the cost effectiveness of building by offsite methods. The results of the present study are from the private housing sector, complementing the DfM experience with social housing. However, the cross-wall costs measured in £/sqft (with the lowest over £100/sqft in Project E) were higher than the targeted maximum construction cost of £72.87/sqft in the DfM projects (Homes and Communities Agency, 2010). This difference occurs because medium to high rise buildings studied in this paper represent more complex designs (medium to high rise apartment buildings) and therefore are inherently more costly than the £60k homes (houses and low rise apartment buildings).

The results also support the findings of the National Audit Office's (2005) study that MMC such as advanced panel (£663–£1104/sqm), hybrid (£675–£1126/sqm) and volumetric (£772–£1287/sqm) other than open timber frame (£599–£998/sqm) continue to be slightly more expensive than more established techniques of 'brick and block' (£599–£999/sqm), but the cost ranges for different techniques overlap substantially. The large overlap means that, in any particular set of conditions, MMC could be as cost effective as 'brick and block', or more cost effective. These calculated cost ranges, albeit not exactly comparable, confirm that the DfM competition to build a home for £60 000 (equivalent to £784/sqm) is a challenge but is within the reach of MMC. The construction costs (with external works/services excluded for effective comparison) of the cross-wall projects in this study typically ranged from £105/sqft to £120/sqft, which are within the cost ranges of advanced panel, hybrid and volumetric techniques reported in the National Audit Office's (2005) study. However, the costs of cross-wall should be more competitive in these comparisons, considering the factors of the time to which the costs were indexed and the design complexity of the buildings. Nevertheless, the construction costs (with external works/services included) of the cross-wall projects (typically ranging from £120 to £135/sqft or £64k to £80k/plot) were far lower than the 'build cost' of the concrete or steel-structured residential towers (ranged from £150 to £200/sqft or £120k to £300k/plot) studied by Knight Frank and EC Harris (Knight Frank, 2004).

Cost evolution of offsite construction

The overall process of utilizing PCC cross-wall technology in the company demonstrated success in achieving a commercially viable (compared to conventional options) construction solution for medium to high rise residential buildings. The process demonstrated cost reductions in projects with similar levels of design and building complexity as well as cost effectiveness in all the projects. The literature of construction cost and building height suggests that unit construction cost tends to rise with building height, with some research reporting an average rise rate of 2% per floor (see Tan, 1999). Although such a rise rate is affected by technology, design, demand and institutional factors and therefore is debateable, the positive correlation is certain. This helps explain the increases of construction cost of both offsite and conventional construction for Projects G and H which were 20 storeys, much higher than the typical nine storeys in the previous schemes. There were also interesting correlations observed between the component costs, i.e. structural work, M&E and fit-out. However, the results do not offer significant enough evidence to support or question the perception that the efficiency gains from using cross-wall structure lead to cost savings in M&E and fit-out work. A possible explanation can be that such cost savings were not realized in the projects or passed on to the developer. Another reason might be that the correlation analysis may be skewed by interactions with other building parameters such as number of storeys and design specifications. Future research, drawing on a larger sample of projects, should enable more meaningful quantitative observations.

The cost evolution of PCC cross-wall systems for the eight projects during the five-year process (2004–08) also shows that competition between manufacturers and suppliers helped bring tender prices of offsite construction towards actual costs of the system. This consequence addresses the concern of Gibb (2001) that many manufacturers and suppliers seek the maximum price that the market will sustain, the tender prices quoted may not reflect the actual costs, and will enable sensible comparisons with conventional construction. More significantly, the cost comparison for the later more complex schemes suggests that partnering, rather than traditional competitive procurement routes, was considered more effective in terms of sustaining the cost reduction and effectiveness of high rise building construction.

Cost engineering means and implications

The identified four cost engineering means all have important implications for managing offsite technology in the organizational context. The importance of the first means, i.e. ‘efficiency learning’, echoes the findings of recent research. For instance, Roy *et al.* (2005), presenting a process documentation system, suggested process review, sharing knowledge and good practice for efficiency improvement in the construction process of housebuilding. Pan (2010) investigated the life cycle of two product innovations and two process innovations comparatively, and illustrated the importance of organizational learning in managing innovation in complicated organizational constructs. Secondly, the means of ‘technological innovation’ (including the four sub-means) helps illustrate innovation as a process, as elucidated by Jones and Saad (2003) that innovation is not a single or an instantaneous act, but a whole sequence of events which occur over time and involve all the activities of bringing a new product or process to the market. This means also addresses the challenges of the management of technological innovation, i.e. ‘complexity, risk and learning’ (Dodgson *et al.*, 2008). Thirdly, the means of ‘in-house’ build management is novel to the business of UK large housebuilders which are normally more focused on land acquisition but engage a main contractor for complex construction (Meikle, 2008). Finally, the means of ‘national and international partnering’ addresses the problems with the parties in the housebuilding sector, e.g. poor communication, lack of supply chain collaboration or integration (see Hong-Minh *et al.*, 2001; Naim and Barlow, 2003), and demonstrates the significance of the commitment of the developer to driving the collaborative journey of pursuing the cost efficiency and effectiveness of offsite construction.

All the means were identified within the context of the housebuilding organization which was committed to exploring offsite and innovative construction methods and utilized offsite methods in a series of projects over years in order to substantiate the benefits/value. Therefore, the cost engineering means were grounded on the practice of large developing/housebuilding organizations (or specialist offsite builders/developers) for repeated projects. Care should be taken by one-off clients (or the like, which are less or not prepared to make serious commitment to offsite construction) when interpreting the results. Given the fact that larger companies (top 100) contributed more than two-thirds of new homes completions in the UK (Wellings, 2006), the take-up of the findings by these firms should enable a step-change in the industry towards an increased take-up of offsite construction. Also, care should be taken in interpreting the results within other built environment sectors than residential.

The application of the cost engineering means also supported the organizational learning of the company with utilizing offsite technology, and contributed to the success in achieving cost savings and cost effectiveness of building by offsite methods. This illustrates the logic of the learning curve or experience curve (i.e. efficiency improves or production costs decline with cumulated output (Ghemawat, 1985)), albeit in a qualitative way rather than being mathematical. After all, as Ghemawat (1985, p. 144) explained, ‘the experience curve is too complex to be encapsulated in simple prescriptions’, and ‘experience curve slopes very widely from product to product’.

Though the research results are focused on the cost of offsite construction, the pursuit of cost efficiency and effectiveness of offsite construction by the company during the five years (2004–08) presents an effective case for developing and implementing a new technology of building. Such a case helps illustrate the 'innovation journey' as defined by van de Ven *et al.* (1999, pp. 6–7) as 'new ideas that are developed and implemented to achieve desired outcomes by people who engage in transactions (relationships) with others in changing institutional and organizational contexts'. The cost engineering means adopted by the company in its journey of exploring offsite technology suggest that the company's management efforts actually went beyond van de Ven *et al.*'s (1999) focus within organizations, towards its external environment markedly reflected by its multinational supply chain. Such expanded concept was elaborated by Geels *et al.* (2008, p. 524), in the context of sustainable innovation, at the level of societies, sectors and nations, as 'to capture the open and uncertain nature of radical technological change, which is full of search and exploration processes, twists and turns, etc'. In this sense, the perceived high capital cost of offsite technology is a type of surrogate risk and uncertainty. The journey of developing PCC cross-wall systems is also a process of ironing out risks and uncertainties, and therefore—by removing their surrogate costs—of achieving residual actual costs of the technology (no absolute real cost, but subject to collaborative negotiation between the developer and its supply chain). This process leads to the adopter's confidence with, and more commitment to, offsite construction.

Conclusions

Offsite construction has long been reported as an effective alternative to conventional construction, with wide-ranging benefits. However, a wider take-up has been inhibited by cost barriers. To address the cost barriers the paper has examined the construction cost performance of pre-cast concrete (PCC) cross-wall panel systems in comparison with in-situ reinforced concrete (RC) frame, steel frame and timber frame methods. The examination was carried out with 20 medium to high rise residential buildings of eight projects carried out by a UK leading housebuilding company during a five-year period from 2004 to 2008. Against the research questions, the paper concludes:

(1) Offsite construction for apartment buildings does not necessarily involve higher construction cost than conventional options. The case of utilizing PCC cross-wall panel systems for medium to high rise buildings was found consistently cheaper than conventional systems including RC frame or steel frame solutions, with construction cost savings ranging from 11% to 32%. The savings mainly existed in reduced preliminary and superstructure costs and eliminated contractor overheads.

(2) The capital cost of offsite construction for apartment buildings can be effectively reduced. The process of adopting, developing and innovating cross-wall technology over the projects led to continuous cost savings, up to 25% from the first use. The use of cross-wall also improved cost effectiveness for high rise buildings for which costs of RC frame and steel frame solutions would increase rapidly and be vulnerable to steel price fluctuations. These cost benefits contribute to offsite approaches' whole-life cost benefit or value over conventional options. The myth of high capital cost or cost intensive investment associated with offsite construction proved unfounded.

(3) The construction cost savings are practically achievable by building organizations through effective management. A number of cost engineering means are identified for sustaining cost reduction and the effectiveness of utilizing offsite methods, which included efficiency learning, technological innovation, partnering, and 'in-house' build management. It is important to develop and use positive relationships between the developer and offsite suppliers to drive cost and design efficiency through collaborative working. The results help illustrate the logic of the learning curve or experience curve in improving efficiency or reducing cost.

The conclusions nevertheless suggest that further investigation in a new context would be merited, e.g. another organization or country. The findings should encourage the practice of offsite construction in the future, and support future research into exploring the adoption and development of offsite technology as an innovation journey in organizational contexts. Sustained cost reduction and effectiveness is not automatically given by using offsite techniques, with time or experience. It requires a long-term commitment of the organizations and continuous exploration of the offsite technology in collaboration with their supply chains. Otherwise, the myth of the higher capital cost of offsite construction will likely turn into reality.

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