TOWARDS A DECISION-SUPPORT TOOL FOR SELECTING AN APPROPRIATE STRUCTURAL FRAME

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ABSTRACT: The selection of the appropriate structural frame for a building during the conceptual design stage is crucial to the overall performance and value delivered to clients. Although several attempts have been made to develop IT-based decision support tools to select the structural frame, these have failed to recognise the importance of 'soft' performance criteria, primarily because of the complexity inherent in the selection process. In reality, structural frame selection is usually based upon heuristic decision-making dominated by subjectivity and qualitative reasoning. Following a thorough review of literature in the building performance domain, a tool that incorporates both 'soft' and 'hard' performance metrics for selecting appropriate structural frame was developed. The tool requires a systematic evaluation of the importance of each criterion and the likely performance achieved using various structural frame options. A worked example is provided to demonstrate how a project team can use this tool. This tool essentially helps to make explicit the most important issues to be considered during the selection process, which should demonstrably lead to improved performance and added value for clients.

Keywords – design process, hybrid concrete construction, performance criteria/ indicators, structural frame

1. INTRODUCTION

In providing the underlying form of a building, protecting occupants against environmental forces and (quite literally) supporting their activities, the structural frame is undeniably an essential element of any building. The appropriate selection of materials, configuration and capacity of such a frame is vital to the short and long-term success of the building. In the short-term, the frame must satisfy the client's needs such as construction completed on time and to budget. In the long term, it must permit, for example, the degree of flexibility required by the same client. The final choice is of particular significance since the frame interfaces with many of the other elements of the building, thereby having a tangible impact on their specification and buildability.

Studies of current practice with regards frame choice indicate that selection criteria tend to focus on cost and time requirements (e.g. Idrus and Newman, 2003). Although these two criteria are important and should not be detached from any business endeavour, they are not sufficient to accommodate various issues related to user needs and requirements pertaining to the service-life of the building. Furthermore, structural frames tend to be selected based on heuristic decision-making processes dominated by subjectivity and qualitative reasoning (Ballal and Sher, 2003). This complexity may be further magnified with the involvement of various stakeholders and consequently affected by their decisions. A more objective and systematic selection process is needed. This would help the construction industry in general to deliver consistent high quality products that better meet client expectations.

Traditionally, construction has long been characterised as suffering from a lack of innovation and slow to adopt new ideas and technology: factors that have been regarded by some as the reasons for a lack of performance (e.g. Egan, 1998). To accommodate ever-increasing user needs and requirements, it is essential that the industry explores new structural frame technologies on offer, such as Hybrid Concrete Construction (HCC), here defined specifically as the combination of in-situ and precast concrete (Goodchild 1995; Glass and Baiche 2001). HCC aims to offer all the benefits of using each individual element, whilst compensating for the individual weaknesses of those same elements. For example, Goodchild (1995) argued that an in-situ reinforced concrete frame is often regarded as the most inexpensive solution, whereas precast concrete promotes speed and high quality. The combined solution has the potential to provide greater speed, quality and overall economy. Nevertheless, authoritative criteria to assess the potential of this technological innovation have neither been clearly defined nor established. Once established, the criteria would allow stakeholders to realise the benefits of using such innovations and thus widen the options available.

This paper proposes a tool for selecting an appropriate structural frame for a given building. The tool comprises a list of criteria which include both 'hard' and 'soft' metrics which may better capture the potential 'value' of structural frames, as opposed to the traditional outturn measures of time and cost. This would help to realise the potential benefits of using new structural frame technology. The criteria were compiled based on a thorough review of literature in the building performance domain. Analysis of survey data suggested that these should be grouped under seven dimensions. The tool requires a systematic evaluation of the importance of each criterion and the likely performance achieved using various structural frame options. A worked example is provided to demonstrate how a project team can use this tool. Used appropriately, the tool should help project teams to better compare alternatives and determine optimal structural frame solutions for given situations, which should enhance the likelihood of their achieving better value.

2. STRUCTURAL FRAME PERFORMANCE CRITERIA

Structural Frame Performance Criteria (SFPC) are those that can be used to measure the performance of structural frames. The intention was to compile a list of empirically derived criteria that could be used to assess a number of aspects in relation to the selection of appropriate structural frame during the early design stages. An extensive review of literature in related areas was conducted since there was no authoritative and comprehensive list of performance criteria specifically developed for assessing structural frames. The reviewed literature included building performance evaluations, Post-Occupancy Evaluations (POEs) and various other construction-related performance indicators. These were meticulously evaluated for their relevance to structural frames and are presented in the first column of Table 1. In total, this examination revealed thirty-one separate criteria that could be used as indicators.

The criteria have two important characteristics. Firstly, SFPC are relevant for evaluating the performance of both the physical construction process and end product (i.e. the building). Secondly, SFPC address both 'hard' and 'soft' issues. The *hard* criteria include cost and speed of construction that are quantifiable in nature and so allow a more objective assessment to be made. In contrast, the *soft* criteria comprise more subjective factors relating to individual perceptions such as confidence and satisfaction with the finished product. Although these are harder to measure, they are more likely to reflect the measures against which new technologies, such as HCC, could prove to be more attractive.

Table 1. Structural frame performance criteria

Performance Criteria	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r
Physical Form and Space																		
The layout, structure and engineering systems are well integrated.								■						■				■
The layout and size work well.		■						■		■	■	■	■	■	■	■		
The circulation works well.		■						■		■	■		■	■	■	■		
The building has sufficient floor to ceiling clear height.										■			■	■				
The building provides appropriate lettable area/spans.																		■
The form is well conceived.								■				■		■				
Construction Process																		
The frame is structurally efficient.								■						■				
The building can be quickly constructed.	■																■	■
The construction costs can be minimised.	■																	■
The building has been designed so it can be safety constructed.	■							■									■	■
The overall risk is perceived to be low.																	■	■
Long-term Sustainability																		
The building is designed for demolition and recyclability.				■	■		■	■										
The building is adaptable to changing needs.								■			■							
The finishes are durable and maintainable.		■						■			■		■	■				■
The form and materials optimise the use of thermal mass.							■										■	■
The facility management (i.e. O & M, replacement) costs can be minimised.		■					■	■								■		
The disposal (i.e. demolition and site clearance) costs can be minimised.				■	■		■	■										
The building minimises environmental impacts (in terms of energy/resource consumptions and waste).		■	■	■	■	■	■	■							■	■	■	■
Establishing Confidence																		
The building enhances the team/client's confidence (in the selected structural frame).																	■	
The design costs can be minimised.																		■
The building is perceived to be simple to build.																	■	■
Building Impact																		
The building reinforces the image of the occupier's organisation.								■		■								
The building reflects the status of the occupier.										■	■							
The building overall meets perceived needs.									■	■								
Physical Appearance																		
The colour and texture of materials enhance enjoyment of the building.								■				■		■				■
The quality and presentation of finishes are good.													■					
The building overall looks durable.																■		
The connections between components are well designed and buildable.																	■	■
The tolerances of the components are realistic.																	■	■
Client Satisfaction																		
The building provides best value.																		■
The client is satisfied with the finished product.	■																	

Note:

a = KPI Working Group (2000)
b = BRE (2000a)
c = Sustainability Working Grp (2001)
d = BRE (2000b)
e = BRE (2001)
f = Arup (2003)
g = DTI, BRE, CIRIA (2003)
h = CIC (2002)
i = Cohen *et al*. (2001)
j = Preiser (1983, 1989, 1995)
k = Carpenter & Oloufa (1995)
l = Sanders & Collins (1995)
m = Bottom *et al*. (1997)
n = Liu (1999)
o = Preiser & Schramm (2002)
p = Douglas (1993/4)
q = Barrett (2001)
r = Glass (2002)

The list of criteria was developed into a questionnaire designed to capture practitioners' perceptions of the relative importance for each criterion. Following a pilot survey to refine the presentation of the criteria, a pilot questionnaire was distributed to a selected sample of practitioners at managerial levels, including experienced clients, contractors, architects, engineers and quantity surveyors. These were based on personal contacts and various databases (Dun and Bradstreet 1998; Estates Gazette 1999; Kompass Directory 1999-2000; Lauren Hill (*ed*.) 1999; CIOB 1998/1999; Knutt and Osborne 1998; RIBA 1998). Overall, 275 questionnaires were distributed and 52 completed, representing a response rate of 18.9 per cent. All of the criteria included in the list were considered to be important, confirming the validity of the criteria as a basis for consideration in the structural frame selection (Soetanto *et al*., 2004a).

The data were used to group the criteria using exploratory factor analysis, which yielded seven principal factors. The finding suggests that SFPC could be interpreted using seven underlying performance dimensions which are 'physical form and space', 'construction process', 'long-term sustainability', 'establishing confidence', 'building impact', 'physical appearance' and 'client satisfaction'. These provide a new paradigm for assessing the performance of structural frames and thus the selection of the best option. Readers may wish to consult Soetanto *et al*. (2004b), for a more detailed discussion about these dimensions.

3. THE ASSESSMENT OF STRUCTURAL FRAME FOR DECISION MAKING

Having compiled and evaluated the SFPC, an important question arose as to how a project team would actually utilise the criteria in practice. The list of SFPC could be used as a basis for a decision support tool in the selection process, but a mechanism is needed to consider all aspects of the structural frame options simultaneously; inputs could be provided by members of project team via a meeting (i.e. brainstorming or value engineering session) during the early project stages. The proposed mechanism firstly requires the 'importance' and the 'performance' of a particular frame option to be stipulated against each criterion. These terms are explained as follows.

3.1 Importance (I)

During this first process, members of the project team would first need to determine the weighting for each criterion in terms of importance (I). This indicates the value or weight for each criterion in relation to: client and project objectives; and influence on the decision-making process for structural frame selection. The project team needs to consider the importance of the various criteria in terms of meeting client and project objectives and the whole process of design, construction, occupation, maintenance and demolition. The level of importance ranges between 0 to 10, indicating a continuum between no importance and extremely important. Here, zero (0) importance indicates the criterion is not related to project objectives and therefore has no impact on the decision (this criterion being subsequently ignored and removed from further calculation). Conversely, an importance value of ten (10) indicates that the criterion is essential in achieving project objectives and hence crucially influences the decision making process. When rating the importance of one particular criterion, it is crucial to consider the relative importance of the others, thereby avoiding a similar level of importance for all criteria (for example, avoid rating all criteria as extremely important and assigning a score of 10). Prioritisation of the criteria into several groups, according to their levels of importance, can help assign reasonable (i.e. workable) importance values for the criteria.

3.2. Performance (P)

Once the project team has agreed on the *Importance* value for each criterion, the evaluation of structural frame alternatives can commence. Here, the project team needs to assess the performance of one alternative against the criteria regardless their importance. The project team needs to agree on the Performance (P) of that alternative for each criterion on a scale of 0 to 10, where 0 means extremely poor and 10 means excellent. The value of P indicates how well a particular structural frame scores against a certain aspect of performance. The values of I and P can then be used to calculate a Performance Weighted Score (PWS) explained in the following. PWS was created to integrate the Importance values into the assessment, allowing those criteria considered more important to be prioritised accordingly.

3.3 Performance Weighted Score (PWS)

The PWS (valued between 0-10) represents a weighted level of structural frame performance, as calculated by the following formula:

$$\sqrt{\mathrm{IxP}}$$

That is, the square root of the product of the level of performance (P) and the corresponding level of importance (I), as indicated by the project team members. The utilisation of the square root is simply to provide meaningful values of PWS between 0-10. Hence, a high score represents a high level of weighted performance and vice versa. Higher PWS means higher likelihood to achieve client objectives.

The PWS for each heading, e.g. *Physical Form and Space*, is the mean PWS for that heading based on the number of relevant criteria derived from:

$$\text{Generic PWS} = \frac{\sum^{n}\sqrt{\mathrm{IxP}}}{n}$$

where n = number of criteria attributable to given generic heading.

Hence, in the worked example presented in Table 2, the average PWS (In-situ concrete) for *Physical Form and Space* is 5.8 (ranging between 0-10), indicating a reasonable PWS for that heading. Note, when a certain criterion is not considered relevant, an importance rating of 0 is allocated and the criterion is subsequently ignored and removed from the calculation.

Finally, overall PWS represents the overall mean total of PWS for a particular frame assessment based on the seven headings, i.e. dimensions, which in the example is 5.1 for in-situ concrete frame, representing an average level of PWS (in this context 'average' is taken as the median value of 5).

4. ASSESSING STRUCTURAL FRAME ALTERNATIVES: A WORKED EXAMPLE

To demonstrate the use of the tool for selecting an appropriate structural frame, a worked example is presented. Suppose that the client, a finance and insurance company, is commissioning a new headquarters in London. The client is well informed about construction technology since they have portfolio of ongoing construction projects. They have contacted an architect well-known for designing offices and headquarters. The architect was then briefed by a team from the company, i.e. the client representative. Although there are cost and time constraints, the building should reflect the status and image of the company. Since the building will be designed for a 100 year-service life, whole life cycle issues such as energy efficiency are likely to be more significant in the future. The architect has developed a concept design but would like to discuss this with other members of project team regarding the future building form and requirements.

A meeting is arranged and attended by client representative, architect, structural engineer, quantity surveyor and contractor. The architect presents a concept design for the project. At this stage, it is ideal to use the proposed tool for selecting an appropriate structural frame from a range of alternatives. The worked example is presented in Table 2. The team discusses the importance of the criteria and proposes three structural frame alternatives for formal evaluation. These are in-situ concrete, steel and hybrid concrete structural frames. The in-situ concrete frame represents a traditional structural technique, whereas steel is perceived as a more modern, faster option. Hybrid concrete is a combination of precast and in-situ concrete. Next, the team evaluates the performance of each alternative against each criterion listed in the tool. Subsequently, the value of PWS for each criterion, heading and overall can be calculated.

In the example shown in Table 2, it is apparent that the priorities of the project team are on ‘building impact’, ‘long-term sustainability’ and ‘physical appearance’ (specifically in terms of colour, texture and finishes) dimensions of the building, which are reflected in their importance scores. ‘Client satisfaction’ is paramount as in any building project. Although constraints, ‘cost’ and ‘time’ aspects are not the main priority. The hybrid concrete structural frame performs better than its alternatives in the highly prioritised dimensions, resulting in higher PWS. Average PWS values for ‘building impact’, ‘long-term sustainability’, ‘physical appearance’ and ‘client satisfaction for the hybrid concrete frame are significantly higher than those for in-situ concrete and steel frames. In terms of ‘physical form and space’ and ‘construction process’, the differences in PWS between alternatives are considered marginal. In the ‘physical form and space’ dimension, the hybrid frame performs better in the well-conceived form criterion, which may be interrelated to ‘building impact’ and ‘physical appearance’ dimensions. In the ‘construction process’ dimension, the steel frame is quicker and less expensive to build than its alternatives. The hybrid frame scores highly on safety due to off-site fabrication of precast components, resulting in a cleaner, tidier site and less on-site activities. In the ‘establishing confidence’ dimension, a steel frame performs better in terms of design cost and perceived simplicity to build criteria. It is worth nothing that an in-situ concrete frame fails to establish the confidence of project team. Overall, based on the PWS, the most appropriate structural frame for this hypothetical scenario is hybrid concrete. The steel frame comes second, whereas in-situ concrete frame is the least favourable alternative.

Table 2. Worked example of tool for selecting appropriate structural frame

Performance Criteria	I	In-situ		Steel		Hybrid	
		P	PWS		PWS		PWS
Physical Form and Space							
The layout, structure and engineering systems are well integrated.	7	5	5.9	6	6.5	7	7.0
The layout and size work well.	6	5	5.5	5	5.5	5	5.5
The circulation works well.	6	6	6.0	6	6.0	6	6.0
The building has sufficient floor to ceiling clear height.	7	7	7.0	7	7.0	7	7.0
The building provides appropriate lettable area/spans.	4	4	4.0	5	4.5	6	4.9
The form is well conceived.	7	6	6.5	4	5.3	9	7.9
Average PWS			**5.8**		**5.8**		**6.4**
Construction Process							
The frame is structurally efficient.	4	3	3.5	8	5.7	7	5.3
The building can be quickly constructed.	4	5	4.5	9	6.0	6	4.9
The construction costs can be minimised.	1	8	2.8	9	3.0	6	2.4
The building has been designed so it can be safety constructed.	7	5	5.9	7	7.0	9	7.9
The overall risk is perceived to be low.	6	3	4.2	5	5.5	7	6.5
Average PWS			**4.2**		**5.4**		**5.4**
Long-term Sustainability							
The building is designed for demolition and recyclability.	6	1	2.4	8	6.9	9	7.3
The building is adaptable to changing needs.	7	6	6.5	8	7.5	7	7.0
The finishes are durable and maintainable.	8	8	8.0	5	6.3	9	8.5
The form and materials optimise the use of thermal mass.	8	2	4.0	1	2.8	9	8.5
The facility management (i.e. O & M, replacement) costs can be minimised.	8	7	7.5	5	6.3	8	8.0
The disposal (i.e. demolition and site clearance) costs can be minimised.	6	1	2.4	5	5.5	8	6.9
The building minimises environmental impacts (in terms of energy/resource consumptions and waste).	8	5	6.3	2	4.0	9	8.5
Average PWS			**5.3**		**5.6**		**7.8**
Establishing Confidence							
The building enhances the team/client's confidence (in the selected structural frame).	7	1	2.6	5	5.9	9	7.9
The design costs can be minimised.	2	4	2.8	9	4.2	6	3.5
The building is perceived to be simple to build.	5	3	3.9	9	6.7	7	5.9
Average PWS			**3.1**		**5.6**		**5.8**
Building Impact							
The building reinforces the image of the occupier's organisation.	9	2	4.2	3	5.2	9	9.0
The building reflects the status of the occupier.	9	3	5.2	2	4.2	9	9.0
The building overall meets perceived needs.	10	3	5.5	4	6.3	8	8.9
Average PWS			**5.0**		**5.3**		**9.0**
Physical Appearance							
The colour and texture of materials enhance enjoyment of the building.	8	3	4.9	4	5.7	9	8.5
The quality and presentation of finishes are good.	8	3	4.9	2	4.0	9	8.5
The building overall looks durable.	8	6	6.9	3	4.9	9	8.5
The connections between components are well designed and buildable.	7	-	-	9	7.9	9	7.9
The tolerances of the components are realistic.	7	-	-	8	7.5	9	7.9
Average PWS			**5.6**		**6.0**		**8.3**
Client Satisfaction							
The building provides best value.	10	4	6.3	6	7.7	9	9.5
The client is satisfied with the finished product.	10	5	7.1	5	7.1	9	9.5
Average PWS			**6.7**		**7.4**		**9.5**
OVERALL PWS			***5.1***		***5.8***		***7.2***

5. CONCLUSIONS AND IMPLICATIONS

The structural frame is a key building element and its performance ultimately determines the success of a building in both technical and human terms. Therefore, selection of the structural frame is a crucial activity in the early design stage. The most commonly used criteria were mainly cost, time and quality. Although these are commonly regarded as key performance criteria, their utilisation is too simplistic in light of the increasingly sophisticated performance issues (e.g. environmental impact, sustainability). Moreover, there is growing concern regarding the need to consider added value and design quality (e.g. aesthetics and 'softer' issues) at early project stages. Furthermore, inputs from all members of the project team are essential for smooth delivery and for judging the overall success of the project. This paper has identified the lack of a systematic method/tool of selecting an appropriate structural frame for a building project. The tool should consider various performance issues and the mechanism for which it can properly be utilised by various stakeholders of the building project.

The developed tool aims to provide a robust and transparent methodology for informing frame choice. It requires the project team to determine the weighting of each criterion, i.e. the Importance (I) and the Performance (P) of a particular structural frame against each criterion. The level of importance indicates the value or weight for each criterion in relation to client and project objectives, and in influencing selection of an appropriate structural frame for a particular building project. The value of P indicates how well a particular structural frame performs against a certain criterion. To integrate the importance values into the assessment, a Performance Weighted Score (PWS) is created. The PWS is then used to calculate scores in each criterion, each heading and overall structural frame performance. PWS provides the basis to select an appropriate structural frame for that particular building project.

The tool can be utilised during a project meeting where team members are allowed to communicate, discuss and rethink their ideas. Hence, the criteria provide a reference for this exercise and specifically, a basis for assessing (i.e. discussing) advantages and disadvantages of structural frame options. It is crucial the team members adopt a proactive and cooperative attitude in dealing with other members and willingly appreciate their ideas, without the presence of a hidden agenda, so that the optimum solution can be achieved to the benefit of all project stakeholders, especially the client. These attitudinal requirements are the backbone of this exercise and should not be overlooked. Failure to adopt this collaborative attitude will undermine the benefits derived from the tool. As a final note, the 'scores' derived from the assessment tool themselves are not critical, but the tool essentially serves as a guide to discuss various performance issues and integrate the various views of stakeholders.

In addition to the work presented here, simultaneous research has been conducted to develop a visualisation model capable of simulating these structural frame performance criteria (see Zhang *et al*., 2004) and to equip the model with accurate 'hard' productivity data (i.e. for time and cost) (see Oloke *et al*., 2004). Collectively, this approach will improve design decision-making processes during early design stages, enabling the project team to conduct what-if scenarios for selecting an appropriate structural frame to better meet the expectation of clients and other members of project team.

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